IMPACTS OF CROSS-REGIONAL MOBILITY OF CONSTRUCTION AND DEMOLITION WASTE IN AUSTRALIA

Huanyu Wu

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

School of Architecture and Built Environment
Faculty of Engineering, Computer and Mathematical Sciences
The University of Adelaide

May 2020

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ACT	Australian Capital Territory
ADP	Abiotic Depletion
AP	Acidification Potential
BIM	Building Information Modelling
C&D waste	Construction and Demolition Waste
C&I waste	Commercial and Industrial Waste
CO_2	Carbon dioxide
Dee	Department of the Environment and Energy
EC	European Commission
EP	Eutrophication Potential
EPA	Environment Protection Authority
EPFL	Swiss Federal Institute of Technology - Lausanne
FAETP	Freshwater Aquatic Ecotoxicity Potential
FOEN	Swiss Federal Office for the Environment
GFA	Gross Floor Area
GIS	Geographic Information System
GISA	Green Industries South Australia
GRI	Global Reporting Initiative
GWP	Global Warming potential
HTP	Human Toxicity Potential
IPCC	Intergovernmental Panel on Climate Change
IPU	Institute for Product Development
ISO	International Standards Organisation
kg	kilogram
LCA	Life Cycle Assessment
LO	Land Occupation
m^3	cubic metre
MAETP	Marine Aquatic Ecotoxicity Potential
MFA	Material Flow Analysis
MJ	MegaJoule
MSW	Municipal Solid Waste
N	nitrogen
NIST	National Institute of Standards and Technology
NSW	New South Wales
NT	Northern Territory

ODP	Ozone Layer Depletion Potential
P	phosphorus
POCP	Photochem, Ozone Creation Potential
QG	Queensland Government
QLD	Queensland
RO	Research Objectives
SA	South Australia
SD	System Dynamics
SEMC	Swedish Environmental Management Council
SETAC	Society for Environmental Toxicology and Chemistry
SLCA	Social Life Cycle Assessment
SO_2	Sulfur dioxide
SV	Sustainability Victoria
t	ton
TAS	Tasmania
TETP	Terrestic Ecotoxicity Potential
TLR	textiles, leather and rubber
UK	United Kingdom
UNGC	United Nations Global
US	United States
USA	United States of America
VIC	Victoria
WA	Western Australia
WGR	Waste Generation Rate
WoS	Web of Science

Abstract

There is a pressing global challenge to manage the massive generation of construction and demolition (C&D) waste, which amounts to over 10 billion tons per year and is part of the largest waste stream in the world. Inappropriate management of waste will generate a series of environmental, economic and social impacts. Recent reports suggest that multiple incentives cause C&D waste to be transported from the region where it was originally generated to other regions for further treatment. This cross-regional mobility will affect the amount of C&D waste being managed in the regions that export and import waste, thereby affecting the environmental, economic and social performance of the system. Previous studies adopted a local-closed theory to study C&D waste and there is little knowledge about cross-regional mobility of C&D waste and related impacts.

To investigate these issues, this research was designed to understand the C&D waste treatment and management from a **novel perspective** addressing the impacts of the cross-regional mobility of the waste. This was done by: (1) investigating the management and cross-regional mobility of C&D waste in Australia; (2) evaluating the impacts of cross-regional mobility by using a **novel methodology** developed in this study; and (3) developing a series of recommendations for the management of C&D waste cross-regional mobility. Sufficient data was collected through a literature review, desktop surveys, site surveys, a series of expert interviews and a seminar, and professional databases to address all objectives.

The study has generated many interesting results e.g., the reporting of in-depth knowledge of and the management status of C&D waste in Australia, including composition and generation, and fates[1] and flows. Similarly, it quantified and mapped the C&D waste cross-regional mobility, including types of waste subjected to mobility, the routes of mobility, and associated regions. In terms of the impacts of C&D waste cross-regional mobility, the study demonstrates that if cross-regional mobility of C&D waste increases the recycling rate, this can reduce environmental impacts and increase industry income. With respect to the social aspect, if a considerable amount of C&D waste generated involved cross-regional mobility, employment opportunities for managing waste in regions that export waste will generally decrease. Based on the findings, ten optimisation strategies have been recommended for management of cross-regional mobility of C&D waste in Australia.

[1] Fates refer to waste treatment methods such as preprocessing, recycling, energy recovery, and landfilling.

This research is a first in Australia in considering cross-regional mobility of C&D waste management. The study offers an innovative research perspective by expanding the C&D waste management theory from the local-closed loop to a cross-regional network level. With respect to methodology, this study also improves management performance assessment methodologies for C&D waste by considering environmental, economic and social impacts of cross-regional mobility of waste. Novel assessment approaches, indicators, calculation methods and databases developed from the study will make a contribution to management performance assessment methodologies for C&D waste. In addition, the state-of-the-art information revealed in the study will enable local C&D waste management service providers to optimise their product category and investments.

Statement of originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of The University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

I acknowledge that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Name: **Huanyu Wu**

Signature:

Date: 10/05/2020

Associated publications

Wu, H., Zuo, J., Yuan, H., Zillante, G., & Wang, J. (2020). Cross-regional mobility of construction and demolition waste in Australia: An exploratory study. *Resources, Conservation and Recycling*, 156, 104710. https://doi.org/10.1016/j.resconrec.2020.104710. (See **Appendix C**). The paper associates contents in Chapter 1, 4, 5 and 7.

Wu, H., Zuo, J., Zillante, G., Wang, J., & Yuan, H. (2019). Status quo and future directions of construction and demolition waste research: A critical review. *Journal of Cleaner Production*, 240, 118163. https://doi.org/10.1016/j.jclepro.2019.118163. (See **Appendix D**). The paper associates contents in Chapter 1 and 2.

Wu, H., Zuo, J., Yuan, H., Zillante, G., & Wang, J. (2019). A review of performance assessment methods for construction and demolition waste management. *Resources, Conservation and Recycling*, 150, 104407. https://doi.org/10.1016/j.resconrec.2019.104407. (See **Appendix E**). The paper associates contents in Chapter 3 and 4.

Wu, H., Zuo, J., Zillante, G., Wang, J., & Yuan, H. (2019). Construction and demolition waste research: A bibliometric analysis. *Architectural Science Review*, *62*(4), 354-365. https://doi.org/10.1080/00038628.2018.1564646. (See **Appendix F**). The paper associates contents in Chapter 2.

Acknowledgements

The PhD is like a journey. Now I am standing at the finish line of this long journey. I would like to take this opportunity to appreciate those lovely people who helped me during this journey.

First of all, my thanks to my supervisors Professor Jian Zuo and Professor George Zillante from the University of Adelaide, and Professor Jiayuan Wang from Shenzhen University. Without your guidance, I would probably have lost my way in the journey.

I would like to appreciate the University of Adelaide for providing the scholarship (Adelaide Scholarship International: ASI-1712146) to support my study. My appreciation also goes to the academic and support staff from Adelaide Graduate Centre and the School of Architecture and Built Environment. Your kindly supports are essential to complete the PhD program.

I also would like to thank Professor Hongping Yuan from Guangzhou University, A/Professor Huabo Duan from Shenzhen University, and Dr Ruidong Chang from the University of Adelaide for their valuable suggestions. I also appreciate the experts participated in the seminar and interviews, and the organisations who hosted site visits.

My special thanks to my father Hao Wu, my mother Leling Tang, my girlfriend Pei Wen at my home country China, and thanks to my colleagues and friends in Australia. Your supports gave me the power to overcome all challenges in this Journey.

I also would like to show my thanks to Dr Diane Brown for copyediting my thesis in accordance with the current ACGR/IPED national guidelines and the Australian Standards for Editorial Practice (2013).

The last but not least, I appreciate the examiners for their time and efforts to add a beautiful ending to this thesis.

Huanyu Wu

10/05/2020

Chapter 1. Introduction

1.1 Introductory background

It is estimated that about 10 billion tons of construction and demolition (C&D) waste are generated annually worldwide (Wu et al., 2019a). Annually, China generates three billion tons of C&D waste (Zheng et al. 2017); the European Union generates over 800 million tons (EC, 2019); and the United States generates about 700 million tons (Jain et al., 2015). By comparison, the amount of C&D waste generated in Australia is significantly less, reaching 20 million tons in 2017, but it is still the most significant stream of all solid waste generated in the country (Dee, 2018).

Although compositions of C&D waste may vary across regions mainly due to the state of the economy, the natural environment and construction practices; masonry waste such as concrete and bricks normally accounts for 70-80% of the total waste (Bernardo et al., 2016; Malia et al., 2013). A small fraction of C&D waste contains hazardous components (e.g. asbestos) that have several impacts on human health, the natural environment and society (Gualtieri, 2013; Roussat et al., 2008). According to the *Australia National Waste Report 2018*, the composition of C&D waste mainly includes masonry (asphalt, concrete, bricks and plasterboard), metals (steel, aluminium and other non-ferrous metals), organics (garden organics and timber), paper and cardboard, plastics, glass, TLR (textiles, leather and rubber), and others (Dee, 2018). An example of C&D waste is shown in Figure 1.1.

Figure 1.1: Example of construction and demolition waste

(Photo taken by the author in Adelaide, 13/02/2018)

Apart from some harmful waste matter and mixed fragments, the majority of C&D waste materials can be recycled, or have energy recovered from them (EC, 2019). In particular, inert C&D waste (e.g. concrete and bricks) can be recycled into aggregate, used mainly in road paving or as recycled materials (e.g. mortar, concrete and bricks) (Garcia-Gonzalez et al., 2014; Vegas et al., 2015). Reports suggest that the overall recycling rate of C&D waste in Australia is around 67% (Dee, 2018, 2019). Similarly, in some Australian States and Territories, the recycling performance is better than the average; for instance, the diversion rate (including recycling and energy recovery) of C&D waste in South Australia reached 91% in 2018 (GISA, 2019), and the recycling rate of waste in New South Wales reached 81% (NSW-EPA, 2019). Australia's recycling rate of C&D waste is higher than other developed countries such as the US (45%) and Norway (41%) (Dee, 2018). The recycling performance of C&D waste in Australia is much higher than many developing regions where the majority of C&D waste is disposed of in landfills (Ajayi et al., 2016; Esa et al., 2017; Wang et al., 2019). To some extent, the Australian experience in managing C&D waste provides valuable information for other countries seeking to improve their waste management performance.

The massive amount of C&D waste that is generated causes a series of environmental issues; such as raw material waste, energy consumption, water and soil pollution, and land occupation. Besides, processing the waste also requires significant financial investment and labour resources (Wu et al., 2019b). On the other hand, managing C&D waste has multiple benefits, such as avoiding landfill and replacing the use of raw materials by recycling, thereby minimising impacts (Lu et al., 2015, 2016). As the largest mass of C&D waste comes from heavyweight and low unit economic value materials (which make the transportation of C&D waste inefficient); these types of waste are normally treated and recycled at local recycling facilities or disposed of in local landfill. Therefore, the management of C&D waste is usually viewed as a local-closed issue by the administrations, and the management system boundary has been limited to the regional level (Wu et al., 2019a, b).

Since Australia is a market-based economy and the Australian Constitution enshrines freedom of trade between states and territories, the industry can determine C&D waste material flow to wherever the best economic outcomes can be achieved (Dee, 2018). In fact, driven by multiple incentives, C&D waste would be transported from the originally generated region to other regions for further treatment. For instance, in recent years, large amounts of waste have been transported from New South Wales (NSW) to Queensland (QLD) for landfill, considering the significant cost difference of waste recycling and disposal between those regions (Dee, 2018).

To respond to the challenge of massive C&D waste generation, significant research and industry led endeavours have been undertaken in these fields. For instance, studies have been conducted to examine waste management practices in major economies such as Canada (Yeheyis et al., 2013), Germany (Karavezyris, 2007), the United States (Warren et al., 2007), the United Kingdom (Soutsos & Fulton, 2016), Switzerland (Spoerri et al., 2009), China (Lu & Yuan, 2010), Australia (Udawatta et al., 2015a), Spain (Rodriguez-Robles et al., 2015) and Malaysia (Esa et al., 2017). Some studies have examined material flows and networks from waste generation to final disposal (Bergsdal et al., 2007; Kucukvar et al., 2014). Furthermore, C&D waste management performance has been evaluated from the perspective of sustainability, feasibility and viability (Jung et al., 2015), and waste management efficiency (Ajayi et al., 2015; Tam, 2008). However, the systematic literature review of this study has revealed that the research perspectives of previous C&D waste related studies was limited to a local-closed scope approach and cross-regional mobility of C&D waste was overlooked in previous studies, despite the latter's significant environmental, economic and social impacts. This limitation of research perspectives in previous models has hampered the understanding of C&D waste management in the discipline. Accordingly, rethinking the system boundaries of C&D waste research and investigating cross-regional mobility can improve this understanding and expand the theoretical development of the field.

Against this background, the main aim of the study is to understand C&D waste treatment and management, particularly cross-regional mobility of waste in Australia. The main objectives of the study in relation to C&D waste in Australia include:

(1) Investigating management and cross-regional mobility;

(2) Assessing impacts of cross-regional mobility; and

(3) Providing recommendations to the government and industry regarding the management of cross-regional mobility.

The study makes three main contributions to the field:

- Firstly, the insider knowledge of C&D waste management in Australia, will provide valuable information to help other countries or regions improve their waste management performance;
- Secondly, it will expand the boundary of C&D waste management theory by tackling the issue from a novel perspective of cross-regional mobility; and
- Thirdly, the novel impacts assessment models proposed will also contribute to the development of sustainability assessment methodologies.

1.2 Statement of the research problem

1.2.1 Investigation of C&D waste generation, flows and management

C&D waste has attracted a lot of attention from scholars in various disciplines, and the issue has been studied from various perspectives. For instance, studies from *the Environmental Science and Engineering* discipline mainly focus on the physical and ecological impacts of C&D waste by studying heavy metals and organic compositions leaching from waste (Denyes et al. 2014); scholars from the discipline of *Material Science* are more interested in reusing and recycling C&D waste, and then testing and improving physical performance such as strength and durability of recycled products (Evangelista & de Brito 2017; Poon & Chan 2006; Tam & Tam 2009). C&D waste management draws attention to and from various disciplines - accordingly it really should be considered as a cross-discipline issue. Similarly, significant research has been conducted in the introduction of waste management practices in different countries (Karavezyris 2007; Udawatta et al. 2015b; Warren et al., 2007; Yeheyis et al. 2013).

Many studies have investigated C&D waste generation worldwide over the last two decades, as waste generation data provides basic information for planning waste management facilities. Previous studies have mainly focused on three aspects:

- Some studies focused on investigating waste generation rates (WGRs) of C&D waste materials (Kern et al., 2015; Li et al., 2013; Lu et al., 2011, 2016; Malia et al., 2013). Multiple methods such as site visits, questionnaires, expert interviews, and desktop surveys were adopted in previous studies to obtain the data on estimating waste generation.
- Another major research cluster concentrated on investigating the generation of C&D waste for different project types. Typically, C&D waste generation for a building can be calculated by multiplying WGRs and the GFA (Gross Floor Area) (Mercader-Moyano et al., 2013; Saez et al., 2013; Solis-Guzman et al., 2009).
- Many studies investigated C&D waste generation in specific countries/regions, such as Norway (Bergsdal et al., 2007), Portugal (Coelho & de Brito, 2011), Spain (Solis-Guzman et al., 2009), the US (Cochran et al., 2007), Malaysia (Lau et al., 2008) and China (Wu et al., 2016a; Zheng et al., 2017).

Tracking material flows of C&D waste is another significant area of research, which is about understanding material flows from waste generation to final disposal. With this information, waste management measures can be applied to minimise waste generation and reduce waste disposal in landfill (Wu et al., 2019b). For instance, Hu et al. (2010) adopted a dynamic material flow approach to analyse C&D waste generated by urban housing in Beijing. Based on C&D waste material flows, environmental impacts can be evaluated i.e. by investigating the C&D waste recycling chain in Italy, Blengini and Garbarino (2010) analysed the energy and environmental implications in the industry. Material flows of C&D waste will sometimes be integrated with other supply chains, and during the planning process of the management system, the dynamics of waste flows should be taken into account when determining C&D waste recycling networks (Hiete et al., 2011). Although many studies of C&D waste generation and flows can be found in Europe, Asia and America, there is no related study of Oceania found in international journals. Hence, investigating C&D waste generation and flows in Australia can redress this gap in the research.

1.2.2 C&D waste cross-regional mobility issues

Depending on the characterisation of C&D waste, the majority of waste consists of masonry material such as asphalt, concrete, bricks and plasterboard (Dee, 2018, Zheng et al., 2018). These materials are heavyweight, and their unit economic values are not very high and transporting them over a long distance is inefficient. This waste is normally treated and recycled at local recycling facilities or disposed of in local landfills (Wang et al., 2018).

Driven by economic incentives or common industry practices, C&D waste can be transported from the originally generated region to other regions for further treatment. Due to the significant cost difference of regional waste recycling and disposal, large amounts of waste has been transported across-regions in Australia in recent years (Dee, 2018). Previously, C&D waste management has been viewed as a local-closed issue; however, more recently cross-regional mobility issues of C&D waste have been revealed in some studies (Li et al., 2018; Wu et al., 2019 a, b). Such cross-regional mobility will affect the tonnage in regional waste management systems, which further affects environmental, economic and social performance.

The concept of cross-regional mobility has been studied in many disciplines. For instance, in the innovation management field, Singh (2008) investigated the relationships among distributed R&D, cross-regional knowledge integration and quality of innovative output by analysing patents from different firms. Song et al. (2003) studied patenting activities of engineers who moved from US firms to non-US firms. Miguélez & Moreno (2015) focused on interactions between regions' absorptive capacity and cross-regional mobility and networks. In the finance field, Chan et al. (2011) examined cross-region capital mobility in China and tracked the degree of mobility and how this mobility has changed over time. In human migration studies, Saarivirta and Consoli (2014) focused on established universities and graduate mobility in Finland, and Alexeev and Chernyavskiy (2018) assessed federal transfers and regional economies in Russia in 2009 and 2014–2015. In the environmental field, Heininen (2005) investigated the impacts of globalisation and climate change on the Circumpolar North by adopting the cross-regional mobility concept. However, cross-regional mobility has been rarely mentioned in construction related research, with the exception of research by Li et al. (2018) on cross-regional mobility of wood materials for construction.

Hence, studies of cross-regional mobility of C&D waste can expand the system boundary of C&D waste management and enable better understanding of the impacts of C&D waste. Changing the perspective from local-closed to cross-regional mobility can also open up another research area for C&D waste research.

1.2.3 Impacts assessment of cross-regional mobility of C&D waste

Cross-regional mobility of C&D waste will have multiple impacts on the waste management sector, as the C&D waste movement will directly affect the amount of waste being treated (SV, 2018a). All waste treatment activities such as transportation, processing, recycling, energy recovery and landfilling will need inputs of natural resources, consumption of energy, money and labour resources, and this will generate certain outputs (Wang et al., 2019). Hence, cross-regional mobility of C&D waste will affect the environmental, economic and social performance of waste processing and recycling systems in regions involved in waste mobility activities.

How this C&D waste problem was to be addressed in terms of economic, environmental and societal perspectives has raised concerns over the years (Yuan, 2013). Although economic considerations were the dominant decision criterion in practice, two other aspects i.e. environmental and social aspects should be also taken into consideration. As stated by Yuan (2013), if a system is capable of dealing with waste effectively, it should be based on appropriate assessments of economic, environmental and social impacts associated with C&D waste generated. In these studies, human health and safety have been recognised as primary concerns (Chung & Lo, 2003); economic efficiency also has significant effects on the performance of waste management systems (Begum et al., 2006; Shen et al., 2009; Zhao et al., 2011). Along with the enhancement of the sustainability concept, social and environmental impacts have been highlighted in assessing C&D waste management performance (Klang et al., 2003; Manowong, 2012). As an important aspect of improving C&D management performance the evaluation of the effectiveness of waste management systems has become a critical issue (Yuan, 2013).

As a result, some efforts have been made to assess C&D waste management performance. Studies were conducted from different perspectives by employing various models (Ajayi et al., 2015; Saez et al., 2013; Tam, 2008). For instance, some studies developed a sustainability assessment model to assess C&D waste management performance, mostly focusing on economic feasibility which has been a main concern of project stakeholders (Begum et al., 2006; Jung et al., 2015; Zhao et al., 2010). Some studies investigated C&D waste management performance from a holistic view, simultaneously covering economic aspects (Ye et al., 2012; Zhao et al., 2011), environmental aspects (Ding et al., 2016; Marzouk & Azab, 2014) and social aspects (Yuan, 2012). In these studies, C&D waste management systems can be defined at different levels (i.e. project and regional levels). Some studies assess different C&D waste management activities during its life cycle, particularly from an environmental perspective (Butera et al., 2015; Mercante et al., 2012; Ortiz et al., 2010; Penteado & Rosado, 2016; Wang et al., 2018).

In these studies, C&D waste is viewed from different perspectives, for example, products, processes or systems; however, as previous studies viewed C&D waste management as a local-closed issue, they did not consider particular parameters for cross-regional mobility when evaluation criteria were developed. It is difficult to determine whether a C&D waste management system is effective if only one dimension (e.g. economic) performs well while other dimensions offer a mediocre performance. By examining existing studies, it is evident that a lack of a systematic performance assessment approach for evaluating the effectiveness of C&D waste management exists regarding environmental, economic and social aspects. Therefore, impacts assessment methodology for cross-regional mobility of C&D waste management would make a timely contribution to management performance assessment methodologies.

1.3 Gaps in knowledge and research questions

Based on the analysis above, gaps in the knowledge of related C&D waste cross-regional mobility issues can be summarised as follows:

- Firstly, a considerable amount of C&D waste material flow in Australia is treated interstate and overseas and there is a lack of investigation of this issue.
- Secondly, this cross-regional waste mobility has multiple impacts, in terms of environmental, economic and social on regions involved in mobility activities. However, these activities and their related impacts have been overlooked in previous studies. There is also a lack of knowledge in terms of how to assess these impacts.
- Thirdly, there is little knowledge regarding how to manage C&D waste cross-regional mobility issues from both academic and practical perspectives.

In response to the above gaps in knowledge, this study is designed to understand the phenomenon of cross-regional mobility of C&D waste in Australia by investigating the issue via multiple approaches. A series of assessment models to evaluate and analyse the impacts of cross-regional mobility of C&D waste on performance in the construction industry in Australia will be developed to tackle the second research gap. Based on these findings, recommendations will be made for the Australian construction waste management sector regarding management of cross-regional waste mobility.

Two critical concepts in the study are explained as:

- ***Local-closed issues*** – C&D waste is heavy and has a low unit economic value thereby making the transport of such waste inefficient. Previous studies have assumed that C&D waste is processed locally rather than transported to other regions;
- ***Cross-regional mobility issues*** – Cross-regional mobility of construction waste means moving waste across state or territory borders (i.e. some C&D waste is transported cross-border to be processed or dumped in other regions). This will have a significant impact on the environment, the economy and society in a sustainable Australia.

The three main research questions to be answered in this study are:

RQ1: What is the current status of cross-regional mobility of C&D waste in Australia?

This question contains four sub-questions:

(1) What types of C&D waste may be subjected to cross-regional mobility?

(2) What quantities?

(3) What are the routes of mobility? And

(4) How is the waste being managed?

Existing reports indicate that some parts of C&D waste were treated interstate or overseas, however there is no truly accurate data available to verify this. The answer to this question could set up the baseline for a cross-regional mobility scenario of C&D waste in Australia. With this baseline, C&D waste recycling networks can be fully expressed and the base scenario for addressing the second and third research questions can then be developed.

RQ2: What are the impacts of cross-regional mobility of C&D waste in Australia? And how can these impacts be assessed?
Cross-regional mobility of C&D waste may have multiple impacts, in terms of environmental, economic and social on regions involved in mobility activities. Due to the lack of previous studies, the research questions presented in this study attempt explore and develop an understanding of impacts from cross-regional mobility of C&D waste as they relate to construction management and waste management disciplines.

RQ3: What optimisation strategies can be developed to increase economic, social and environmental resources?
Cross-regional mobility is another treatment strategy for generated C&D waste. The answers to this question can enable government, the construction industry and the waste management industry to create further strategies to encourage or discourage cross-regional mobility of C&D waste.

1.4 Research aim and objectives

The aim of this study is to understand the phenomenon of cross-regional mobility of C&D waste, and to analyse the impacts of this phenomenon for the Australian sector of C&D waste management, to decide whether cross-regional mobility should be encouraged or discouraged and at what level.

- **Objective 1: To investigate the management and cross-regional mobility of C&D waste by developing a cross-regional C&D waste material network for Australia.**
    - This network consists of categories, amounts and travel routes of C&D waste being treated interstate or overseas. This objective can be also viewed as the expanded presentation of current C&D waste treatment networks in Australia, since the existing reports only provide the information of waste generation amounts and treatment rates of waste in each state.

- **Objective 2: To develop a novel methodology to assess the impacts of cross-regional mobility of C&D waste by considering economic-social-environmental aspects.**
    - Cross-regional mobility is another treatment route for C&D waste that distinguishes it from regular local-closed treatment methods for waste. Numerous natural resources such as energy and water, as well as financial and labour will be involved in this activity. As the impact assessment of cross-regional mobility of C&D waste is a new question for the discipline, evaluation criteria are needed to develop environmental, economic and social aspects.

- **Objective 3: To provide recommendations to Australian C&D waste management departments to decide whether or not to encourage cross-regional mobility of waste, and at what level.**
    - Cross-regional mobility of C&D waste management is not necessarily a negative phenomenon for the regions involved, and it has some positive effects if managed appropriately. By comparing different scenarios, optimisation strategies can be identified to assist government and industry to make better decisions for the sustainable management of C&D waste.

1.5 Significance of the research

This study is significant as it explores a new issue for C&D waste management from a novel perspective and contributes to the development of theories in the discipline. Apart from theoretical contributions, this study also provides a series of benefits for government, industry and the general public based on the recommendations proposed in the study.

Firstly, this study is innovative by expanding C&D waste management theory from the local-closed loop to a cross-regional network.

Due to the nature of C&D waste, its heavyweight and low unit economic value makes the transportation of C&D waste inefficient and previous studies assumed that the waste was being managed at local facilities. This is simply not always the case and, driven by multiple incentives a significant amount of C&D waste is involved in cross-regional mobility. For instance, 85% of metal waste and a considerable amount of other C&D waste material generated in South Australia has been treated interstate and overseas (GISA 2017). Cross-regional mobility of C&D waste may have multiple impacts on both the waste-exporting and waste-importing regions. These impacts may be seen from the environmental, economic and social aspects as waste mobility is directly related to the amount of waste treated, which informs the investment and resource input of waste treatment facilities. As previously discussed, C&D waste has become a global issue and has attracted much attention from scholars in different disciplines. For example, significant research has been conducted to introduce waste management practices in different countries; follow-up studies track material flows and networks from waste generation to final disposal; and some studies assess C&D waste management performance (e.g. sustainability, feasibility and viability, effectiveness and efficiency). C&D waste is thus perceived from different perspectives, for example, products, processes, or systems, but **all of these previous studies viewed C&D waste as a local-closed issue.** This limitation has impeded the understanding of C&D waste management in the discipline. Therefore, the study is significant, as it expands the research perspective of the discipline by transferring the current local-closed loop problem to a cross-regional mobility network.

Secondly, this study also improves management performance assessment methodologies for C&D waste by considering impacts of cross-regional mobility.
Management performance assessment of C&D waste has been an important topic in this discipline for some time. The previous literature can be summarised in four categories of assessment: sustainability, feasibility and viability, effectiveness and efficiency, and single or combined management performance parameters (i.e. environmental, economic and social) performance. For instance, evaluation criteria for studies on sustainability assessment of C&D waste management mainly focus on environment, economic and social aspects; feasibility and viability assessment of C&D waste management mainly consider the economic aspect; effectiveness and efficiency evaluation of C&D waste management employs diversity evaluation criteria, (e.g. accuracy, eco-efficiency, economic efficiency and multiple index); other studies then present performance assessment of C&D waste management by combining parameters - environmental, economic and social - or by using a single parameter (e.g. environmental, economic or social performance). Due to the aforementioned limitation of the research perspective, viewed as a local-closed management issue, these scholars did not consider particular parameters for cross-regional mobility when they developed their evaluation criteria for C&D waste management.

As a result**, there is a lack of methodology on how to assess the impacts of C&D waste cross-regional mobility in the discipline.** Therefore, the impacts assessment methodology of cross-regional mobility will make a contribution to the development of management performance assessment methodologies for C&D waste.

Thirdly, this study is significant because it has environmental, economic and social benefits.

The waste management and resource recovery sector is a significant contributor to the Australian economy. It has an annual turnover of approximately AUD $12.6 billion, contributing more than 0.43% to Gross Domestic Product (GDP) (directly and indirectly) and employs some 50,000 people (full-time equivalent). Clearly, C&D waste cross-regional mobility directly relates to the amount of waste treatment required. This can be seen in environmental, economic and social divisions. An informed understanding of cross-regional mobility of C&D waste will thus determine investment and resource inputs of waste treatment facilities. The Australian federal government could then understand whether cross-regional mobility of C&D waste has a negative impact and thus make an informed decision to either encourage or discourage cross-regional mobility. Local government departments could benefit when making policy to manage and guide the C&D waste treatment industry in terms of waste mobility by learning from this study; local C&D waste treatment enterprises can also benefit from the development of Australian cross-regional C&D waste material networks with the uptake of knowledge about economic, social and environment resources invested in the network. This vital information can help local C&D waste treatment enterprises to optimise their product category and resource investments. The general public can also benefit from optimisation activities conducted by governments and the C&D waste industry, including better environmental surrounds and increased job opportunities.

1.6 Thesis organisation

This thesis is divided into eight chapters: **Chapter 1** *(Introduction)* presents the background, research objectives, and significance of the research. **Chapter 2** *(Literature review: Part 1)* presents the first part of the literature review, which states the gap in knowledge in research on C&D waste management. This includes the overall status of C&D waste research, main strands of C&D waste research and gaps in knowledge in the field. **Chapter 3** *(Literature review: Part 2)* presents a methodological review of research on the performance assessment of C&D waste management. This review compares the main methods for assessing C&D waste management performance, introduces crucial indicators for assessment models and a framework for C&D waste management performance assessment. **Chapter 4** *(Methodology)* presents the research methodology for this thesis, including the research framework, investigation of management and cross-regional mobility of C&D waste in Australia, development of the impacts assessment models for C&D waste cross-regional mobility, and the development of optimisation strategies for C&D waste cross-regional mobility in Australia. **Chapter 5** *(Results: Part 1)* presents the first part of the results regarding management and cross-regional mobility of C&D waste in Australia. The main results include the composition and generation of C&D waste, the fates and flows of C&D waste, and C&D waste cross-regional mobility in Australia. **Chapter 6** *(Results: Part 2)* presents the second part of the results regarding environmental, economic and social impacts of cross-regional mobility of C&D waste in Australia. **Chapter 7** *(Discussion)* presents the discussion of the results and recommended optimisation strategies for the management of cross-regional mobility of C&D waste in Australia. **Chapter 8** *(Conclusions)* concludes the thesis by highlighting the contribution of this research to understanding the issues of cross-regional mobility of C&D waste in Australia including the findings, theoretical and practical implications, opportunities for future research and finally, closing remarks.

Chapter 2. Literature review: Part 1

2.1 Introduction

For any academic study, reviewing prior and relevant literature is essential. A good literature review creates a solid foundation for advancing knowledge in a certain area by facilitating theory development and identifying the plethora of research that exists and potential future directions. Hence, the review is a critical feature for accelerating development of the discipline (Webster & Watson, 2002). According to Webster and Watson (2002), there are some common structures for executing a review. Firstly, a literature review is needed to provide a working definition of key variables and set boundaries. Secondly, the relevant literature via appropriate data sources needs to be identified. Thirdly, the literature via a concepts-centric approach needs to be analysed. Fourthly, structuring the review based on the sense-making concept and writing the review using an appropriate tone (not overly critical) and effective tense (present or past tense). All these steps should extend or develop theories—the most critical part of a review.

Compared to other methods such as the expert review, systematic literature review methodology has many good features and some weaknesses (Grant & Booth, 2009). Firstly, the literature review should not be affected by the location for conducting the research. Basically, the researcher can conduct a review in the office, library or even at home. Secondly, unlike the expert review which may require huge research resources, including academic and industry networks, a systematic literature review enables more straightforward access to the data. Thirdly, when conducting a literature review, the researchers can refine the search and analysis by time, while it is unlikely that the expert review will be repeated over time (Randolph, 2009).

However, there are also some weaknesses in systematic literature reviews. Firstly, it's time-consuming work and may take several months from the initial reading to written completion (Zopounidis & Doumpos, 2002). A good literature review should be digging in a certain area to extract in-depth information. Considering the overwhelming number of published articles and time spent on reading, analysis and writing, the review cannot always keep up with updated knowledge in the field. Secondly, a literature review can hardly capture all published articles due to the limitation of the database (Boote & Beile, 2005). There are always some fruitful articles hiding in some less popular journals, which may not be included in one well-known database such as Web of Science or Scopus. To address these issues, the review conducted in this study adopts two strategies: updating the search and using multiple databases.

To understand C&D waste and related management issues, and then identify research gaps, a bibliometric analysis and in-depth contents review were conducted. Bibliometric analysis is presented in section 2.1.1 and the method for in-depth review is detailed in section 2.1.2. Based on the review, an overview of C&D waste management is presented in section 2.2. The overall status of C&D waste research based on bibliometric analysis is discussed in section 2.3 and main strands of C&D waste research based on the in-depth contents review is discussed in section 2.4. Finally, key research gaps in C&D waste management knowledge are analysed in section 2.5. **The contents of this chapter have been published in associated publications 2 and 4 listed on page xiii.**

2.1.1 Bibliometric analysis

Currently, a number of databases are available such as PubMed, Scopus, Web of Science (WoS), and Google Scholar for indexing research articles. Falagas et al. (2008) suggested that WoS has the highest coverage in the natural science and engineering field and good coverage in terms of social science, arts and humanities (Mongeon & Paul-Hus, 2016), which is regarded as critical for extracting articles both in waste management and waste recycling techniques. By revisiting the journal list identified by previous review articles on C&D waste, it is found that most of these journals have been included in the WoS database. Therefore, WoS is considered the main source for article searching and filtering. Scopus and Google Scholar are used for updating and adding fruitful articles.

This study used the *Advanced Search function* provided by the WoS core collection database for initial sampling. The search was carried out on 1st March 2018 with the following model: *(TS= ("construction waste" OR "demolition waste" OR "construction and demolition waste" OR "C&D waste")) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article); Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=All years.* Initially, a total of 1,027 articles published from 1992 to 2017 were retrieved from the Web of Science database.

A comprehensive procedure was followed in this study to conduct bibliometric analysis of C&D waste publications (see Figure 2.1).

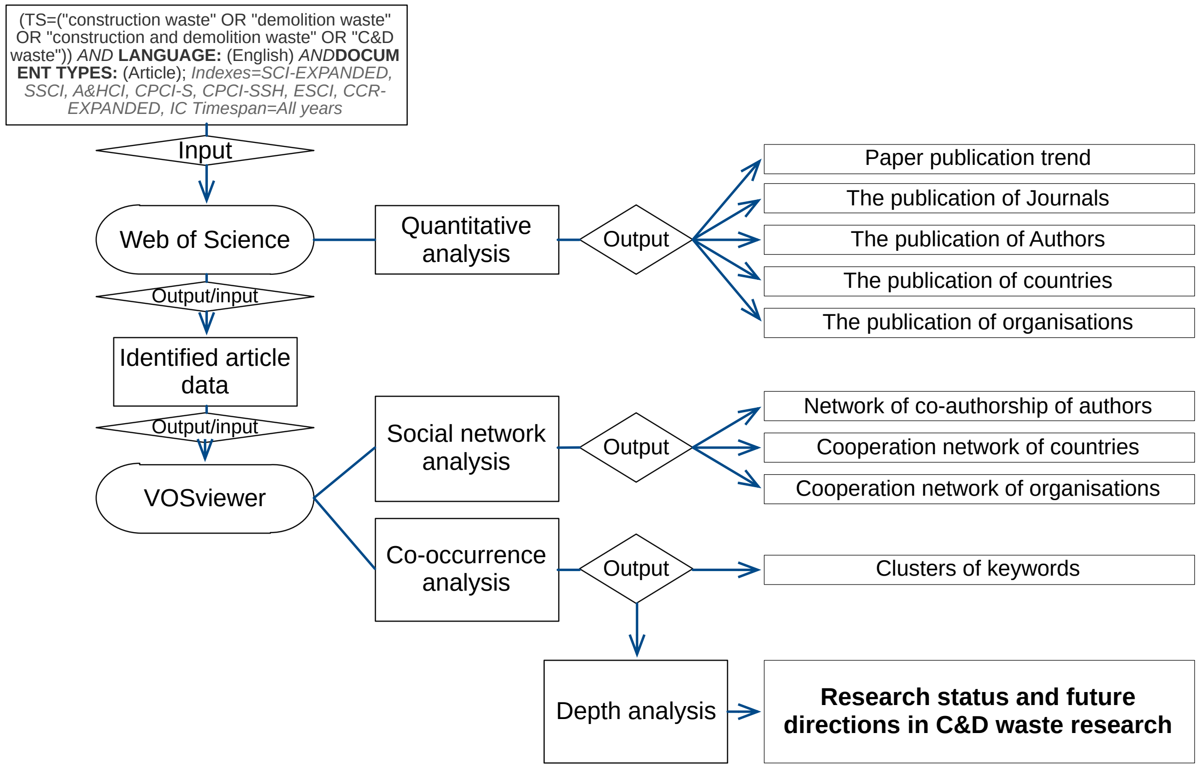


Figure 2.1: Bibliometric analysis of C&D waste publications

Firstly, a basic bibliometric analysis was carried out to quantitatively understand the overall research status of C&D waste. Bibliometric analysis has been widely adopted to map the existing literature and measure research progress in a given field (Raan, 2005). Aspects of the body of literature using the bibliometric analysis method include both quantitative information and qualitative data (Wang et al., 2016). In particular, it includes quantitative and visual processes to identify patterns and dynamics in scientific publications (Pritchard, 1969). In this study, a series of quantitative analyses were conducted to understand the overall status of C&D waste, which will be presented in section 2.3.

Secondly, social network analyses were conducted to depict the relationships among authors, countries and organisations. Social network analysis is designed to model the dynamics between focus and the relationships employed in bibliometric analysis studies (Prell, 2012). In the context of bibliometric analysis, this method has been employed to highlight relationships between various nodes in the networks (e.g. countries, institutions and authors in a given subject) (Wang et al., 2016). This is completed by using user-friendly software, VOS-viewer. Normally, these analyses are based on several rules including: co-authorship analysis, meaning that the relatedness of items is determined based on the number of co-authored articles; co-occurrence analysis, meaning that the relatedness of items is determined based on the number of articles in which they occur together; and full counting referring to each co-authorship, co-occurrence and bibliographic coupling link that have the same weighting.

Thirdly, cluster analysis was carried out to examine the comprehensive relationship between keywords in articles. The approach has been used to search management information systems and analyse research trends, discover research hotpots (Du et al., 2015) and identify the evolution of research topics (Li et al., 2011). Since data visualisation plays a crucial role in network research (Wang et al., 2016), the cluster map was conducted through VOS-viewer as well. To better identify keywords and their relationships, some common words (e.g. construction, demolition, deconstruction, building construction, construction project, construction sector, road, urban, city, construction industry, waste, construction waste, demolition waste, construction and demolition waste, C&D waste, solid waste, construction materials) and region/country names (e.g. the US, UK, Australia, Hong Kong, China, Portugal, Japan, Malaysia, Norway, etc.) have been eliminated.

2.1.2 In-depth contents review

After downloading articles identified from the initial sample selection, the articles were read and analysed via two stages. During March and April 2018, initially selected articles were quickly searched by title and abstract. The purpose of this step was to extract fruitful articles and classify them into different themes and concepts. From May to July 2018, the extracted articles were critically reviewed, and themes and concepts were structured according to the research focus. Finally, 156 C&D waste-related research articles were critically reviewed (see Table A-2.1 in Appendix B), and five broad themes, including ten concepts, were identified and analysed.

Initially, several broad research themes covering the general range of C&D waste research interests were identified, mainly environmental, technical, materials, management and industrial ecology aspects. By analysing the contents of selected articles, concepts were determined to match identified themes. During this procedure, themes were extended and combined to match the concepts identified based on the critical review.

Based on the critical review of selected articles, the conceptual model for main strands of C&D waste research was developed. By examining the research questions, research methods, and main findings and contributions of previous studies, critical knowledge gaps in the current research were identified. By extending current theories and concepts in prior studies, potential research opportunities were proposed for future research. Based on these works, the review was structured and written during August and September 2018. Since the article reading, analysis and review structuring and writing took some time, it was necessary to update the sample. *Google Scholar* was chosen to track the latest publications in the C&D waste research field.

2.2 Overview of C&D waste and management

Based on the review, it is found that a large amount of construction and demolition (C&D) is generated worldwide every year, much of which has the potential to be recycled (EC, 2017). It is estimated that over 10 billion tons of C&D waste are generated worldwide annually, among which the United States contributes about 700 million tons (Jain et al., 2015), the European Union over 800 million tons (Ajayi et al., 2016), and China around 2.3 billion tons (Zheng et al., 2017). Although compositions of C&D waste may vary among regions due to different economies, the natural environment and construction practices, mass of heavy wastes such as concrete and bricks normally constitutes 70-80% of total waste (Bernardo et al., 2016; Malia et al., 2013). In particular, inert C&D waste (e.g. concrete and bricks) can be recycled into aggregate, used mainly for paving roads or as input for recycled materials (e.g. mortar, concrete and bricks) (Garcia-Gonzalez et al., 2014; Vegas et al., 2015). Only a small fraction of C&D waste contains hazardous components (e.g. asbestos) severely impact human health, the natural environment and society (Gualtieri, 2013; Roussat et al., 2008). Therefore, it has become a pressing global challenge to manage and control C&D waste.

To respond to such a challenge, significant endeavours have been undertaken on C&D waste. For instance, studies have been conducted to examine waste management practices in major economies such as Canada (Yeheyis et al., 2013), Germany (Karavezyris, 2007), the United States (Warren et al., 2007), the United Kingdom (Soutsos & Fulton, 2016), Switzerland (Spoerri et al., 2009), China (Lu & Yuan, 2010), Australia (Udawatta et al., 2015a), Spain (Rodriguez-Robles et al., 2015) and Malaysia (Esa et al., 2017). Some studies have attempted to examine material flows and networks from waste generation to final disposal (Bergsdal et al., 2007; Kucukvar et al., 2014). Furthermore, C&D waste management performance has been evaluated from the perspectives of sustainability, feasibility and viability (Jung et al., 2015), and waste management efficiency (Ajayi et al., 2015; Tam, 2008). Given that solutions to waste minimisation can be related to waste recycling techniques (Park &Tucker, 2017; Tam & Tam, 2008), the physical and ecological impacts of C&D waste have been investigated by assessing and handling heavy metals and organic compositions leached from waste (Denyes et al., 2014), as well as by testing and improving physical performance such as strength and durability of recycled products (Evangelista and de Brito, 2017; Poon & Chan, 2006; Tam & Tam, 2009).

2.2.1 Definition and composition of C&D waste

Since C&D waste has attracted attention from industry, the academy and government, significant efforts have been made to minimise waste generation and reduce related environmental, economic and social impacts (Wu et al., 2019b). The definition of C&D waste has not reached a consensus across nations, states and even within the research field. Generally, C&D waste refers to waste generated from building-related construction and demolition activities (Karavezyris, 2007; Lu & Yuan, 2010; Warren et al., 2007), but in some regulations and studies, C&D waste also includes building renovation waste and waste generated from civil engineering projects such as roads, tunnels and railways (Rodriguez-Robles et al., 2015; Udawatta et al., 2015a, b).

Regarding the composition of C&D waste, many articles and reports documented that this waste mainly included materials such as concrete, brick and block, tiles, glass, timber, plastics and asphalt (Bernardo et al., 2016; Malia et al., 2013). As some studies take waste generated from civil engineering projects into consideration regarding C&D waste, its composition would also include extracted soil and stones (Coelho & Brito, 2013). Theoretically, the majority of C&D waste composition is recyclable materials (EC, 2017), but in reality most C&D waste ends up being transported to landfill in developing countries such as China, Indian and Brazil (Zheng et al., 2017), compared to a considerable higher recycling rate (60%-90%) in developed countries such as Japan, Australia and some Western European countries (Karavezyris, 2007; Soutsos & Fulton, 2016; Warren et al., 2007).

As there is no agreed global definition and classification standard for C&D waste, researchers from different countries and regions have various thoughts in terms of definition and composition of C&D waste. Currently, such waste is used more as an abstract symbol and its definition determined by detailed description in published articles or reports. Hence, it is sensible to review previous studies to gain a deeper understanding of the character of C&D waste, including recyclability, material flows and mitigation of pollutant composition from C&D waste.

2.2.2 Attributes of C&D waste

It is widely recognised that C&D waste presents a critical environmental issue. However, C&D waste may be taken into consideration from different perspectives by researchers from different disciplinary backgrounds. On the one hand, researchers from environmental science and engineering fields normally consider C&D waste as a solid waste issue. Hence, they normally address the issue through methods adopted from solid waste management. In fact some studies identify the pollutant composition of C&D waste (Duan et al., 2016; Oygard et al., 2005; Shin & Kang, 2015), and develop measures to control and mitigate such pollution (Bergersen & Haarstad, 2014; Kim & Yang, 2002).

Researchers from other fields, such as material science and engineering and management science, normally recognise C&D waste as an inherent issue in the construction industry (Begum et al., 2007). Therefore, the issue is mostly related to construction activities and stages in the industry. For instance, Ajayi et al. (2016) indicated that in order to divert C&D waste from landfill, cultural change was needed in the UK construction industry. There are also studies claiming that the utilisation of recycled aggregate in prefabrication may have the potential to reduce C&D waste (Jaillon et al., 2009; Li et al., 2014; Tam et al., 2015).

The C&D waste issue has been viewed either as a subject, or a system. Typically, researchers from environmental science, environmental engineering, and material science and other engineering fields tend to consider C&D waste as a subject (i.e. waste or product). They examine C&D waste through experiments to understand its composition in terms of environmental pollutants and recyclability, to control pollution or improve recyclability (Belagraa et al., 2017; Duan et al., 2016; Tam et al., 2007).

Researchers from industrial ecology and management science fields consider the C&D waste issue from a system perspective. A common assumption is that it should be learnt as a system from the development of recycling system (Brattebo et al., 2009; Dosho, 2007). Therefore, several systematic methods, such as system dynamics, have prevailed in dealing with the C&D waste issue. For instance, Yuan and Wang (2014) developed a system dynamics model in order to decide the most appropriate fee for the disposal of construction waste. Tam et al. (2014) investigated C&D waste management at a city level through developing system dynamics models, as well as conducting model simulations.

2.3 Overall status of C&D waste research

Bibliometric analysis has been a useful tool to gain an overall understanding about a given research field, which has provided further insights not fully grasped or evaluated previously. With this approach, the overall development of publications in the field can be quantitatively and systematically analysed. It provides visual graphics to quickly understand the main study strands for scholars, especially those initiating research in particular fields. A series of quantitative analyses were conducted to understand the overall status of C&D waste. The analyses included: (1) article publication trends; (2) distribution of published journals; (3) analysis of authors; (4) analysis of countries; and (5) analysis of author organisations.

2.3.1 Number of published articles

2.3.1.1 C&D waste articles annually publication status

Through the WoS search, 1,027 C&D waste related articles were published between 1994 and 2017 (see Figure 2.2). Before 2007 the number of annual articles was less than 20, but that number has increased eight times in the past decade, reaching 178 in 2016 and then dropping to 176 in 2017.

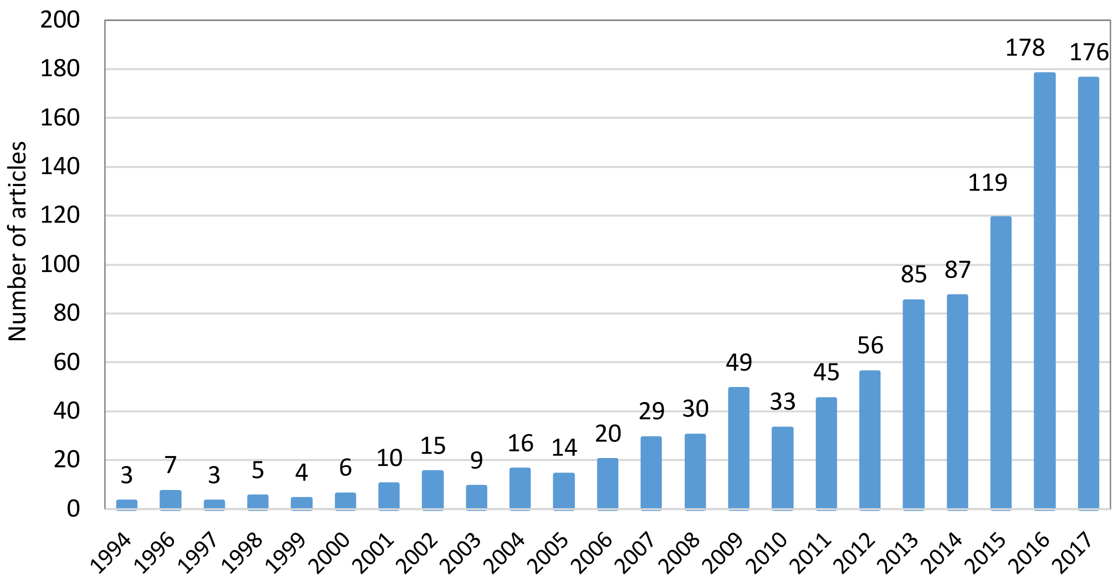


Figure 2.2: Number of C&D waste articles published, 1994–2017

2.3.1.2 Journals publishing most C&D waste articles

The results in Figure 2.3 show that more than half of the C&D waste related articles were published in ten journals, in particular, *Construction and Building Materials* and *Waste Management* each published more than 100 articles, and the *Journal of Cleaner Production* and *Resources Conservation and Recycling* each published more than 50 articles. These journals make a significant contribution to the dissemination of C&D waste research.

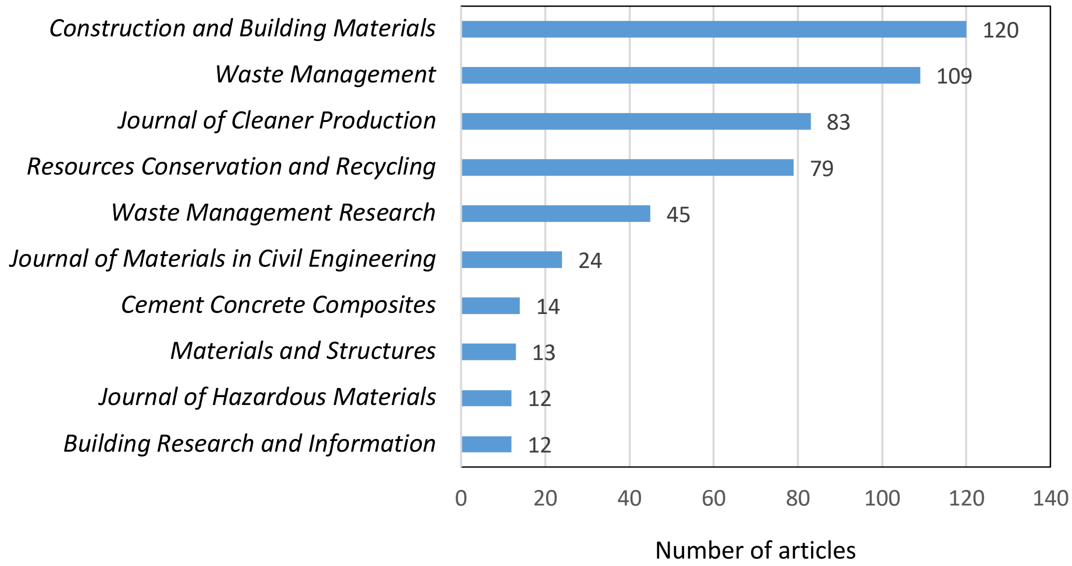


Figure 2.3: Ten journals publishing most C&D waste articles

2.3.2 Publishing performance

2.3.2.1 Number of articles by authors

The results show that during between 1994 and 2017, 74 authors were significant in having C&D waste research published, each with more than 5 articles published (see Table 2.1). Among the top 10 most productive authors, De Britto published 48 articles (1,289 citations), followed by Tam (28 articles, 618 citations) and Poon (22 articles, 639 citations).

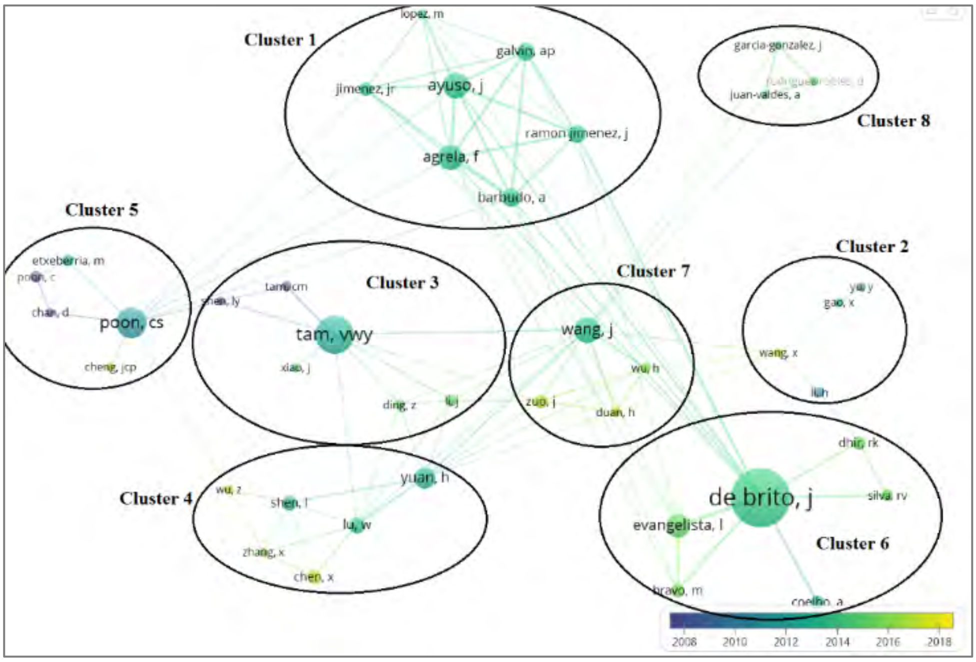
Table 2.1: Authors with most C&D waste articles published

(Ranking based on number of articles published)

Authors	Affiliation	Region	Number of articles	Citations
De Britto, J	University of Lisbon	Portugal	48	1289
Tam, VWY	Western Sydney University	Australia	28	618
Poon, CS	Hong Kong Polytech University	Hong Kong, China	22	639
Ayuso, J	University of Córdoba	Spain	18	351
Wang, JY	Shenzhen University	Mainland China	18	301
Agrela, F	University of Córdoba	Spain	17	383
Evangelista, L	University of Stavanger	Norway	16	325
Perez, I	University of A Coruña	Spain	14	134
Yuan, HP	Southwest Jiaotong University	Mainland China	14	447
Barbudo, A	University of Córdoba	Spain	12	199

2.3.2.2 Co-authorship

Figure 2.4 shows the network of co-authorship in C&D waste research. It can be observed that the network mainly consisted of 8 clusters based on authorship analysis. Each cluster is developed around one or two core authors. Cluster 1 (Agrela and Ayuso) links closely with Cluster 5 (Poon) and Cluster 6 (De Brito). Clusters 3, 4 and 7 are Tam, Yuan and Wang. The network map below clearly shows the most active research groups and authorship relations contributing to C&D waste research.



Note: The size of the node is determined by the number of published articles

Figure 2.4: Network of authorship in C&D waste research

2.3.3 Analysis of author regions

2.3.3.1 Number of articles and citations by region

Table 2.2 shows the top 10 regions contributing to C&D waste research. China has a leading position led in both the number of published articles and citations in C&D waste research. Spain is also influential with 150 published articles and 2156 citations. It is notable that although some regions published more articles, their total citations are less, for example, Brazil with 61 published articles but only 567 citations. This list for the regions contributing to most C&D waste research is quite different from the findings in a study conducted almost a decade ago (Yuan & Shen, 2011), when developing regions such as China, Spain and Brazil did not publish many articles. This reveals a significant geographical change of C&D waste research within the last decade.

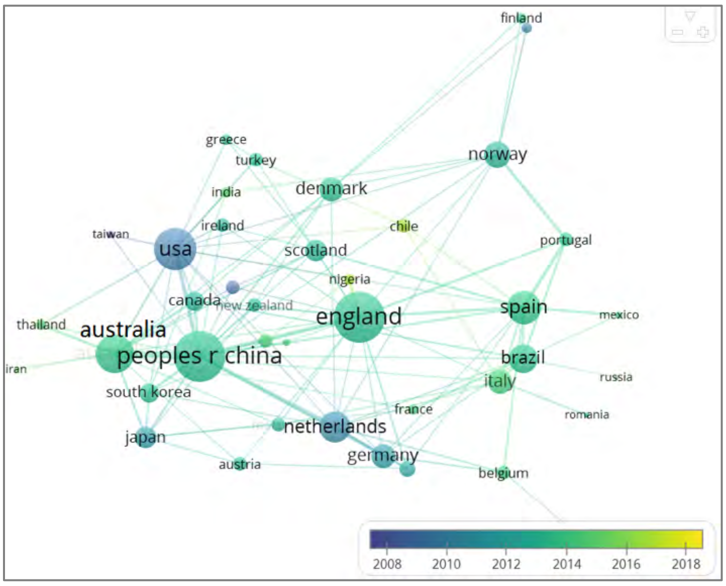
Table 2.2: Regions contributing to most C&D waste research

(Ranking based on number of articles)

Regions	Number of articles	Citations
China	199	3465
Spain	150	2156
Australia	86	1224
England	69	1011
USA	68	1353
Brazil	61	567
Portugal	59	1370
Germany	41	689
The Netherlands	39	803
Italy	37	616

2.3.3.2 Co-authorship among regions

Figure 2.5 shows co-authorship among regions in C&D waste research, which represents the cooperation network among authors from different regions. The size of the nodes is determinate by the strength of links; that is, a region with a larger node means it cooperates more with C&D waste scholars from other regions. The results show that the node size of England is almost equal to that of China although England only publishes a third of articles compared to China. In contrast, the node size of Spain is comparatively small considering its large number of published articles. It reveals that China, England, the USA and Australia are quite active in building cooperative networks with scholars from other regions. In relation to time trend, the USA, the Netherlands, Germany and Japan started researching C&D waste earlier and their main outputs were around 2008, while China, England, Australia, Spain and Brazil followed this trend and their outcomes were mainly around 2014.



Note: The size of the node is determined by the strength of links

Figure 2.5: Research cooperation network among authors from different regions

2.3.4 Analysis of author organisations

2.3.4.1 Publications of organisations

According to the analysis, a total of 925 organisations worldwide have published C&D waste articles, among which 57 organisations have published more than 5 articles (see Table 2.3). The Hong Kong Polytech University in China is the top contributor with 65 articles and more than 2,000 citations. Furthermore, three organisations, including the University of Lisbon in Portugal, Shenzhen University on Mainland China and the University of Córdoba in Spain also contribute significantly, with 27, 25 and 25 articles published respectively.

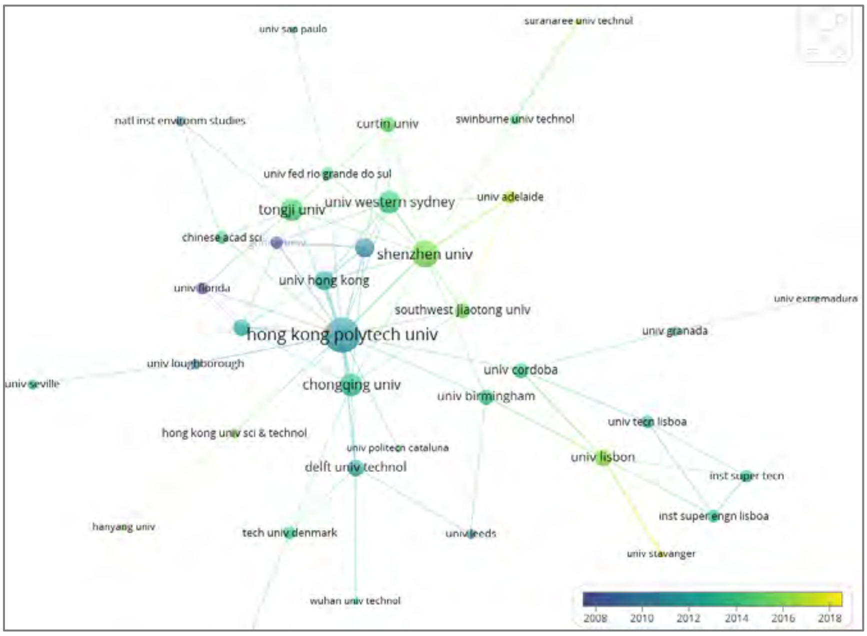
Table 2.3: Organisations publishing most C&D waste articles

(Ranking based on number of articles)

Author organisation	Number of articles	Citations
Hong Kong Polytechnic University, Hong Kong, China	65	2094
University of Lisbon, Portugal	27	274
Shenzhen University, Mainland China	25	315
University of Córdoba, Spain	25	462
Delft University of Technology, The Netherlands	19	163
Technical University of Lisbon, Portugal	18	693
University of A Coruña, Spain	18	155
Western Sydney University, Australia	17	241
Tongji University, mainland China	17	206
The University of Hong Kong, Hong Kong, China	16	459

2.3.4.2 Co-authorship among author affiliations

The cooperative relationship among author organisations is also analysed (see Figure 2.6). Similarly, the size of the node is determined by the strength of links; that is, an organisation with a larger node means it has more cooperation with other organisations in C&D waste research. The results show some Chinese institutions (e.g. Hong Kong Polytech University, Shenzhen University, Tongji University, Chongqing University and University of Hong Kong) tend to build more cooperation with other institutions. Australia's Western Sydney University has also built more comparative links with other institutions. In contrast, some institutions from Portugal (e.g. University of Lisbon, Technical University of Lisbon) and Spain (e.g. University of Córdoba, University of A Coruña) seem to be more inclined to conduct C&D waste research internally, with less links with other institutions.



Note: The size of the node is determined by the strength of links

Figure 2.6: Research cooperation network among institutions

2.3.5 Cluster analysis based on key words

Based on results of the cluster analysis, keywords in C&D waste articles can be classified into five clusters (see Figure 2.7). (Detailed keyword clusters can be found in Table A-2.2 in Appendix B.) They are: *Cluster (1) Environmental concerns of C&D waste; Cluster (2) Recyclability of C&D waste; Cluster (3) Performance and behaviour tests of recycled products; Cluster (4) C&D waste management; Cluster (5) C&D waste from an interdisciplinary perspective*. Subsequently, these clusters are discussed in detail to construct a holistic view of state-of-the-art C&D waste research.

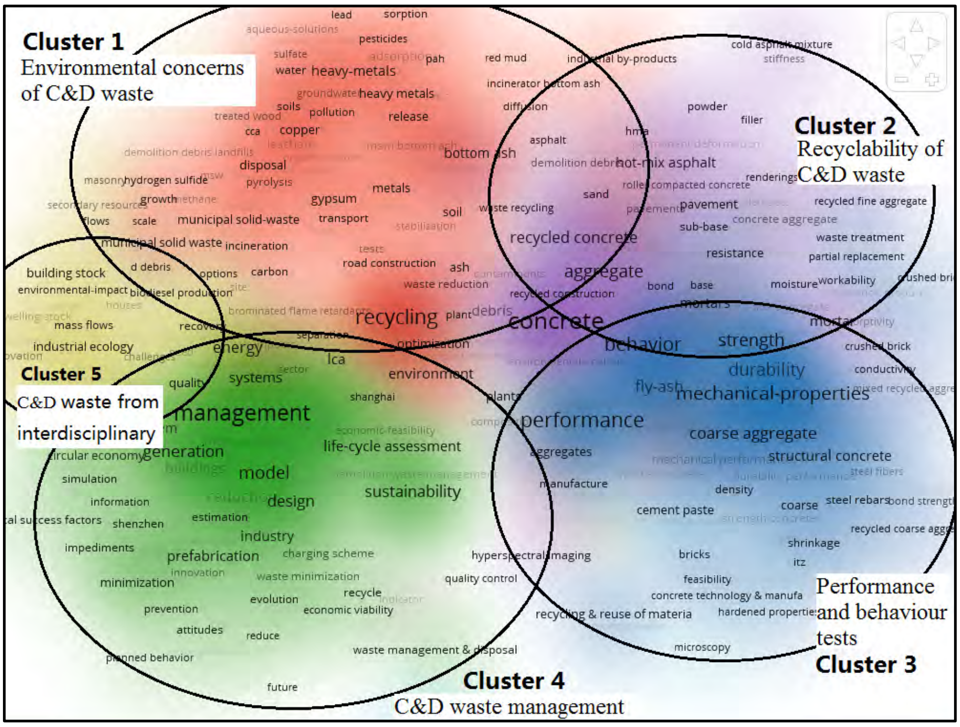


Figure 2.7: Cluster analysis based on key words

Cluster (1) Environmental concerns of C&D waste

The first cluster is related to environmental concerns of C&D waste, which received significant attention from the environmental science and engineering discipline. According to keywords identified in the cluster analysis, articles in this cluster attempted to answer three main questions: (1) What pollutant compositions are contained in C&D waste? (2) How do the pollutants in C&D waste affect the surrounding environment? (3) What measures can be developed to control and mitigate the pollution of C&D waste composition? Existing studies have reported that C&D waste may contain multiple pollutant compositions (e.g. heavy metals and organic matter) (Jang & Townsend, 2001; Praagh & Modin, 2016). These pollutant compositions affect the surrounding environment (e.g. water, groundwater, soils) via multiple mechanisms (e.g. sorption, absorption, release, immobilisation, incineration, pyrolysis, etc.) and approaches (e.g. leachate, biomass, landfill gas, etc.) (Lee & Yun, 2008; Shin & Kim, 2016). There are two main research aspects in this area: (1) Identification of pollutant composition of C&D waste (Duan et al., 2016; Jang & Townsend, 2001; Praagh & Modin, 2016); (2) Control and mitigation of pollution for C&D waste (Delay et al., 2007; Iden et al., 2008; Shin et al., 2016).

Cluster (2) Recyclability of C&D waste

The second cluster is related to recyclability of C&D waste, mostly conducted from the perspective of material science. According to keywords identified in cluster analysis, studies under this cluster mainly focus on the following questions: (1) What recycled products can be made from C&D waste? (2) What are the application situations for C&D waste recycled products? (3) What measures can be developed to test the performance of recyclable waste materials and recycled products? It is widely recognised that some C&D waste materials (e.g. concrete, mortar, brick and glass) are recyclable. For instance, concrete and brick can be used to produce recycled aggregate (Garcia-Gonzalez et al., 2014; Vegas et al., 2015); mortar can be used to produce recycled sand (Ulsen et al., 2013). Recycled C&D waste products (e.g. aggregate, sand, crushed brick aggregate and glass blends) can be used in different contexts (e.g. pavement base or subbase, hot mix asphalt, mortar components, additional materials). Previous studies have focused on three main aspects: (1) understanding recyclable C&D waste materials (Garcia-Gonzalez et al., 2014; Vegas et al., 2015); (2) understanding recycled products of C&D waste (Hou et al., 2016; Kumar, 2017); and (3) making use of C&D recycled products (Arulrajah et al., 2013; Belagraa et al., 2017; Xuan et al., 2016).

Cluster (3) Performance and behaviour tests

The third cluster is related to performance and behaviour tests of waste materials and recycled products from environment science and material science fields. According to keywords identified in cluster analysis, studies under this cluster mainly focus on the following questions: (1) How does C&D waste or recycled products behave? (2) How can the performance of C&D waste or recycled products be examined? and (3) How can the performance of C&D recycled products be improved? Studies have been conducted to test the performance of C&D waste and recycled products (particularly recycled aggregate) (Anastasiou et al., 2014; Belagraa et al., 2017; Silva et al., 2014; Tam et al., 2015). These studies have been conducted from various perspectives such as efficiency of utilisation, physical and mechanical properties/performance and mechanical behaviours. In addition, other aspects such as macroscopic and microstructural properties of recycled concrete have been studied. Some studies, however, focus on specific performance testing (e.g. deformation, tensile strength, compressive strength, resistance, durability, stiffness, etc.) of recycled aggregate. These studies can be classified into two groups: (1) developing performance test indicator systems for testing the performance of recycled products (Belagraa et al., 2017; Matias et al., 2013; Silva et al., 2014; Zega et al., 2010); (2) Conducting specific performance tests, such as strength, durability, stiffness, etc. (Silva et al., 2015b; Tam et al., 2015).

Cluster (4) C&D waste management

The fourth cluster is related to C&D waste management. According to keywords identified in cluster analysis, studies under this cluster mainly focus on the following questions: (1) How can the generation of C&D waste be estimated? (2) How can the generation of C&D waste be minimised? (3) How can the performance of C&D waste management system be assessed? and (4) How can information technology tools be applied in C&D waste management and recycling? Appropriate management measures can help to reduce waste generation, enhance reuse and recycling of waste and minimise waste disposed of in landfill. This can further reduce environmental concerns caused by the massive amount of waste generated. C&D waste management studies can be divided into four groups: (1) quantifying C&D waste generation, including conducting surveys of in particular regions (Bergsdal et al., 2007; Wu et al., 2016a,b; Zheng et al., 2017), investigating the rate of waste generation (Li et al., 2013; Lu et al., 2015, 2017; Malia et al., 2013), and developing C&D waste generation estimation models (Won et al., 2016; Wu et al., 2016b); (2) reducing the generation of C&D waste via management measures (Lu & Yuan, 2010; Wang et al., 2010, 2014); (3) assessing management performance of C&D waste (Coelho & de Brito, 2013; Jung et al., 2015; Zhao et al., 2010); and (4) adopting information technology in C&D waste research (Lu et al., 2016; Wu et al., 2016b).

Cluster (5) An interdisciplinary approach to C&D waste

The fifth cluster relates to C&D waste from an interdisciplinary perspective. This cluster is comparatively smaller and takes an interdisciplinary approach, combining the environment, economy and management. Industrial ecology concerns multiple issues in the system, such as material flows, life cycle impacts and the dynamic of technology in industry (Erkman, 1997). Based on the characterisation of these keywords, studies in this field attempted to answer the following questions: How does C&D waste flow from generation to final disposal? What are the impacts generated in the life cycle of C&D waste? How can the trends or dynamics of C&D waste be better understood? Currently, studies in C&D waste from an industrial ecology perspective mainly focus on the following aspects: (1) Tracking C&D waste materials flow from waste generation to final disposal (Blengini & Garbarino, 2010; Hu et al., 2010; Huang & Hsu, 2003; Wiedenhofer et al., 2015); (2) Life cycle assessment, including developing models to assess life cycle impacts on processing C&D waste (Marzouk & Azab, 2014; Simion et al., 2013) and (3) assessing life cycle energy and resource efficiency in processing C&D waste (Mercader-Moyano et al., 2013; Rivero et al., 2016; Wang et al., 2018; Wu et al., 2015).

2.4 Main strands of C&D waste research: current status

Based on the in-depth contents review, selected articles in the sample can be classified into five main strands according to the research foci, which differ slightly from cluster analysis based on keywords (see Figure 2.8). They are: (1) environmental concerns of C&D waste – from environmental science and environmental engineering perspectives; (2) C&D waste recycling – from a material science and engineering perspective; (3) addressing the sustainability of C&D waste – from an industrial ecology perspective; (4) improving C&D waste management – from a management science perspective; and (5) reducing C&D waste – from architecture, engineering, construction and operation of buildings perspectives. In the following section, these main strands will be discussed in detail to formulate a holistic review of the existing body of knowledge on C&D waste.

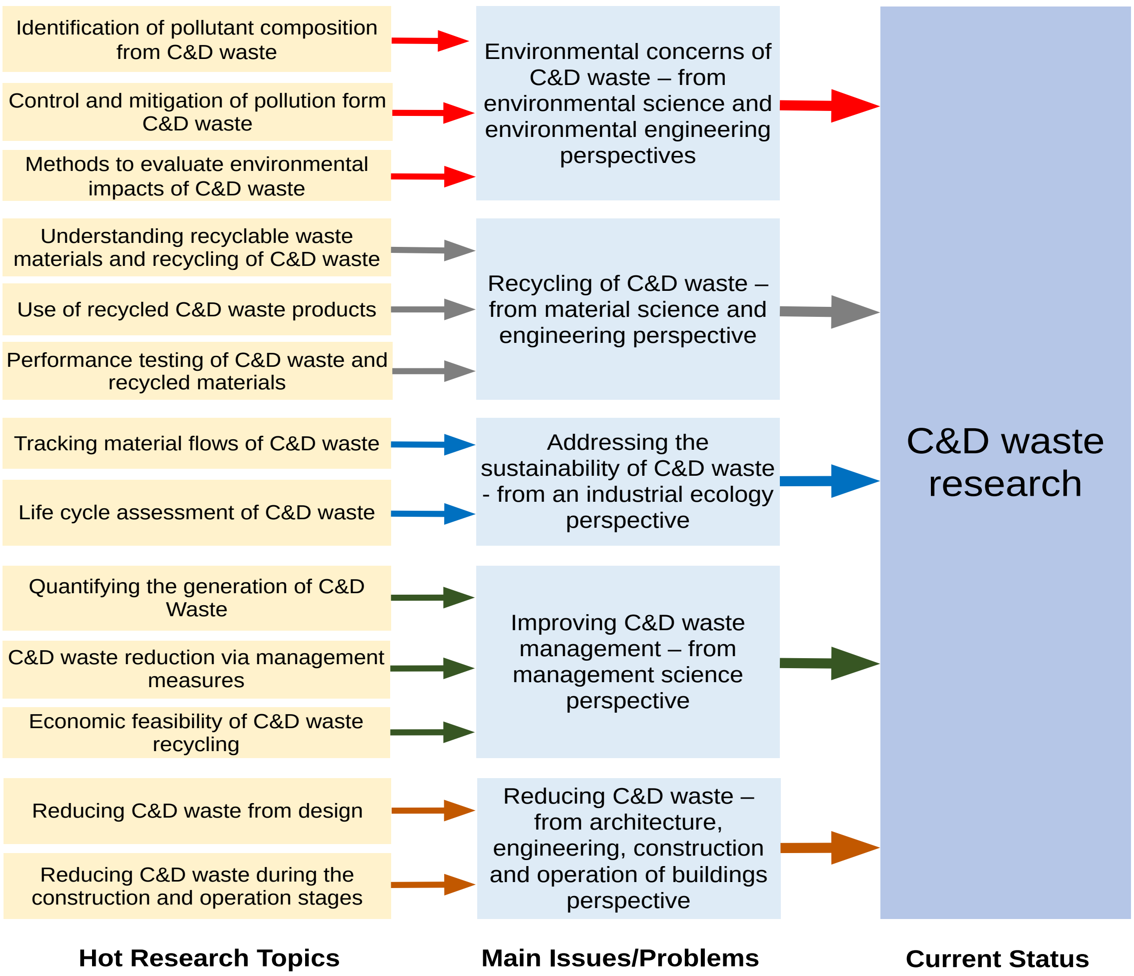


Figure 2.8: Main strands of C&D waste research

2.4.1 Environmental concerns of C&D waste – from environmental science and environmental engineering perspectives

The most common environmental concern that relates to C&D waste is the pollution of overland water (Ferguson & Male, 1980), groundwater (Lee et al., 2008), and soils (Cabalar et al., 2016; Kalbe et al., 2008). These issues have received wide attention from scholars with environmental science and environmental engineering backgrounds. These studies attempt to examine environmental impacts of C&D waste by testing the pollutant composition of waste and analysing the mechanism for how pollutants in C&D waste affect the total environment.

2.4.1.1 Identification of pollutant composition from C&D waste

Identification of pollutant composition from C&D waste plays an essential role in understanding environmental concerns. C&D waste composition may contain multiple pollutants, such as heavy metals (e.g. copper and chromium), and organic matter (e.g. polycyclic aromatic hydrocrack (PAH), carbon, methane, sulfuret and hydrogen sulphide) (Jang & Townsend, 2001; Van Praagh & Modin, 2016). Efforts have been made to identify and quantify heavy metals released from C&D waste and associated impacts on the surrounding environment (Oygard et al., 2005). Some studies assessed effective rates of heavy metals released from such waste (Wehrer & Totsche, 2008), whilst others have concentrated on heavy metal migration measures (Shin & Kang, 2015). Overall, the research in this area is relatively solid, as many results emerge from experimental studies in laboratories in leading universities and institutes. However, since the selection of samples were limited to residential/commercial project sites and landfill which mainly received C&D waste generated from these projects, some toxicity pollutants have been overlooked. Recently, some toxicity organic matter components such as polycyclic aromatic hydrocrack (PAH) and hydrogen sulphide have been found in mixed C&D waste derived from the demolition of industry buildings such as pesticide factories (Duan et al., 2016). The composition and properties of mixed C&D waste are complex. As a result, the environmental and health risks associated with industrial C&D waste are of significant concern (Huang et al., 2016, 2017).

2.4.1.2 Control and mitigation of pollution from C&D waste

In order to control and mitigate pollution from C&D waste, studies have been conducted on the mechanism of sorption, absorption, release, immobilisation, incineration, and pyrolysis (Delay et al., 2007; Iden et al., 2008; Shin et al., 2016). Long-term monitoring (Johnson et al., 1999) revealed that C&D waste landfill produced liquids such as leachate, containing multiple biomass and generated landfill gas. Bergersen and Haarstad (2014) found that mixed demolition waste containing gypsum based plaster- board in landfill generates hydrogen sulphide (H2S) gas, which is typical for landfill gas and major odorant landfill. The removal of nitrogen and organic substances from landfill has become a critical issue. Hence, it is imperative to introduce technical measures for minimising the release of pollutants from C&D waste disposal sites.

2.4.1.3 Methods to evaluate environmental impacts of C&D waste

The occurrence of keywords showed that "leaching test" has been frequently adopted to test pollutants and related environmental impacts (Engelsen et al., 2017; Van Praagh & Modin, 2016). Leaching tests have been studied extensively and leaching in the laboratory environment could closely approximate the waste disposal site where C&D waste makes contact with runoff from rainfall. Galvin et al. (2012) compared leaching tests in batches while their study focused on how pH value may affect the mechanism of metal released from C&D waste. Similarly, Kruger et al. (2012) conducted experiments on how heavy metals and PAH may be released from waste through leaching. However, as leaching behaviour can change dramatically and can be sensitive to different environments, a single test method may not be accurate enough to evaluate the environmental impacts of C&D waste, particularly tracing highly toxic pollutants. This is due to the potential risk that such pollutants within hazardous C&D waste could be released when mixed with other waste materials in landfill (Roussat et al., 2008).

2.4.2 Recycling of C&D waste – from material science and engineering perspectives

C&D waste recycling is another active research area, conducted mostly from the perspectives of material science and engineering. Detailed research topics mainly include: understanding recyclable waste materials and recycling of C&D waste, use of recycled C&D waste products, and performance testing of recycled products from C&D waste. Table 2.4 shows recyclable C&D waste materials, recycled products and use of recycled products identified in previous literature.

Table 2.4: C&D waste materials, recycled products and use of recycled products

C&D waste materials	Recycled products	Use of recycled products	Typical studies
Concrete	Recycled aggregate	Pavement Base/Subbase	Garcia-Gonzalez et al., (2014); Gomes et al., (2015); Vegas et al., (2015)
		Hot mix asphalt (normally made with recycled concrete aggregates coated with bitumen emulsion)	Gomez-Meijide et al., (2016); Rafi et al.,

			(2014); Pasandin & Perez, (2013)
Mortar	Recycled sand	Mortars	Miranda et al., (2013, 2014); Ulsen et al., (2013)
Brick	Crushed brick aggregate	Pavement base /Subbase	Hou et al., (2016)
Glass	Recycled glass blends	Pavement Base/Subbase (adding glass blends into mortar and concrete to improve physico-mechanical performance)	Arulrajah et al., (2014); Kralj, (2009); Penacho et al., (2014)
--	Mixed composite powder materials	Cementitious materials in small-scale prefabricated concrete	Xue et al., (2016)
--	Mixed recycled components (e.g. recycled mixed fine aggregate)	Fillers	Belagraa et al., (2017); Choudhary et al., (2016)

2.4.2.1 Understanding recyclable waste materials and recycling C&D waste

C&D waste materials (e.g. concrete, mortar, brick and glass) have attracted most attention, whereas concrete and brick are usually crushed and made into recycled aggregate (Garcia-Gonzalez et al., 2014; Hou et al., 2016; Kumar, 2017; Vegas et al., 2015). Mortars are usually crushed and made into recycled sand (Stefanidou et al., 2014; Ulsen et al., 2013). Cement mortar adhered on the surface of aggregate is viewed as undesirable, and thus needs to be removed from recycled aggregate (Tam et al., 2007). Glass is considered to have great recycling potential (Arulrajah et al., 2014; Kralj, 2009; Penacho et al., 2014). Considering the number of studies on recycling C&D waste, the previous studies on recycled aggregate and concrete dominated the theme, as masonry waste accounts for almost 90% of C&D waste generation by weight. Compared to other waste materials such as glass, timber and plastics, this type of waste is technically easier to be recycled and economically feasible due to economies of scale. As a result, the treatment of remaining waste fractions has been overlooked and this may seriously impact human health and the natural environment, as some unclassified materials contain hazardous components (e.g. asbestos) (Gualtieri, 2013).

2.4.2.2 Use of recycled C&D waste products

Recycled C&D waste products (e.g. recycled aggregate, recycled sand, crushed brick aggregate and recycled glass blends) can be used in different contexts. For instance, recycled aggregate is frequently used in concrete, large volumes in pavement base or subbase (Arulrajah et al., 2013; Kumar, 2017; Leite et al., 2011; Xuan et al., 2016) and while good quality recycled aggregate has also been used to produce pre-cast and structural concrete (Tam et al., 2018).

The recycled concrete aggregate can be used to produce hot mix asphalt while bitumen emulsion is used for coating (Gomez-Meijide et al., 2016; Pasandin & Perez, 2013). As a recycled product screened from the crushing of mortar, recycled sand can be used as a mortar component (Miranda et al., 2013, 2014; Stefanidou et al., 2014; Ulsen et al., 2013).

Besides, crushed brick aggregate and recycled glass blends can be used as additional materials for some applications. For example, it can be used to form the base of asphalt pavement (Hou et al., 2016). Similarly, recycled glass blends can be added to mortar and concrete to improve physical-mechanical performance (Kralj, 2009; Penacho et al., 2014). This applies to Pavement Base/Subbase as well (Arulrajah et al., 2014). In addition, Xue et al. (2016) introduced the utilisation of C&D waste composite powder materials (e.g. recycled sand blends) in prefabricated concrete.

Although various applications of recycled C&D waste products have been developed, they are mainly based on recycled aggregate related products due to economic feasibility. In fact, other materials can also be used in some applications. For instance, mixed, recycled components have been used as fillers (Belagraa et al., 2017; Choudhary et al., 2016). Timber can be used in land reclamation, soil improvement and urban development. These applications have been applied in practice for years but have not been documented in prior studies which limits the development and application of recycled C&D waste.

2.4.2.3 Performance testing of C&D waste and recycled materials

A number of studies have been undertaken to test the performance of C&D waste and recycled materials (particularly recycled aggregate). Performance evaluation has been undertaken from various perspectives such as efficiency of utilisation (Anastasiou et al., 2014; Ho et al., 2013), physical and mechanical properties/performance (Belagraa et al., 2017; da Silva et al., 2014; Matias et al., 2013; Zega et al., 2010), and mechanical behaviours (Corinaldesi & Moriconi, 2009; Gao et al., 2017; Tam et al., 2015). In addition, other aspects such as macroscopic and microstructural properties of recycled concrete have also been studied (Li & Yang, 2017).

Some studies focus on specific performance testing (e.g. deformation, tensile strength, compressive strength, resistance, durability, stiffness, etc.) of recycled aggregate in concrete. For instance, Tam et al. (2015) investigated deformation behaviour of recycled aggregate from a long-term perspective whereas Silva et al. (2015b) focused on tensile strength behaviour. Sim and Park (2011) examined compressive strength and durability resistance for recycled aggregate concrete. Both fly-ash and fine recycled aggregate were considered useful when mixed with concrete. Other studies investigated durability of multiple recycled products including: concrete consisting of recycled aggregates (Bravo et al., 2015; Lovato et al., 2012), fine recycled aggregates (Vieira et al., 2016), cold asphalt emulsion mixtures (Nassar et al., 2016), recycled ceramic aggregates (Correia et al., 2006), blended cements (Bjegovic et al., 2012) and recycled lime powder (Kanellopoulos et al., 2014). In addition, stiffness is a common performance indicator (Gomez-Meijide et al., 2016).

Studies on performance testing of C&D waste and recycled materials are usually a part of bigger research projects, with a focus on recycling C&D waste. These studies can be viewed as additional research support for original research on recycling C&D waste. Since studies on materials and structures have been conducted for decades, the research methods used in those studies are traditional and solid; however, new approaches are rarely seen in updated articles.

2.4.3 Addressing the sustainability of C&D waste -- from an industrial ecology perspective

Considerable C&D waste studies have been undertaken from the perspective of industrial ecology. As an interdisciplinary approach, industrial ecology concerns various issues in industrial systems such as material flows, life cycle impacts and dynamics of industry technology (Erkman, 1997).

2.4.3.1 Tracking material flows of C&D waste

In the context of industrial ecology, the dynamics of C&D waste are highlighted. To better understand this issue, many efforts have been devoted to tracking waste material flows (i.e. from waste generation to final disposal). For instance, Huang and Hsu (2003) incorporated resource and material flow analysis to investigate Taipei's urban sustainability. Blengini and Garbarino (2010) analysed energy and environmental implications in the C&D waste recycling chain in Italy. Wiedenhofer et al. (2015) examined non-metallic minerals in the EU in terms of stocks and flows. Understanding the trends and dynamics of C&D waste processing is another focus. For instance, Hu et al. (2010) analysed the urban housing system in Beijing, following a dynamic material flow approach. Hiete et al. (2011) argued that the C&D waste recycling network should be considered an integral part of the supply and demand chain at the regional level where its dynamics should be taken into account during the planning process. Although many studies have tried to address this issue, dynamic material flows of C&D waste are still unclear. There are not many effective ways, apart from the bottom-up waste management data report practice, to collect waste flow data. This method can hardly provide accurate waste flow data as the authority only documents waste generated within their administrative region, with few accurate data on waste transported from other regions. The cross-regional transport of C&D waste makes material flows more dynamic, which further affects the accuracy of tracking material flows of C&D waste.

2.4.3.2 Life cycle assessment of C&D waste

The main purpose of studying life cycle assessment of C&D waste is to promote the construction industry's sustainability. This is because the generation of C&D waste is during two crucial life cycle stages (i.e. construction and demolition) and other stages (e.g. design and operation) of building and infrastructure (Blengini, 2009), and thus the management of waste affects performance during the whole life cycle of the project. Thus, a life cycle assessment approach is applied to C&D waste studies (Kucukvar et al., 2016; Mercante et al., 2012; Wu et al., 2015), mainly focusing on:

- *Developing models to assess life cycle impacts of processing C&D waste.* Several studies developed impact assessment methods and indicators to assess impacts of C&D waste treatment (i.e. environmental impacts, economic impacts and social impacts). For instance, Simion et al. (2013) calculated the mechanism of environmental impacts of C&D waste. Marzouk and Azab (2014) evaluated the economic and environmental impacts of two alternatives (i.e. recycling or disposing) for managing C&D waste. Sou et al. (2016) evaluated impacts of current and potential C&D waste management scenarios from environmental, economic, social and regulatory aspects. Duran et al. (2006) assessed the impact of subsidies and environmental taxes on the financial viability of C&D waste recycling.
- *Assessing life cycle energy and resource efficiency of processing C&D waste.* Life cycle energy and resource efficiency of C&D waste has been investigated in different countries, such as the European Union (Rivero et al., 2016), Spain (Mercante et al., 2012), Italy (Blengini & Garbarino, 2010; Vitale et al., 2017), the USA (Diyamandoglu & Fortuna, 2015), and China (Wang et al., 2018; Wu et al., 2015). In terms of resource efficiency of C&D waste, Mercader and Ramirez (2013) quantified the consumption of materials during the construction stage of residential buildings, and Spoerri et al. (2009) proposed strategic planning for C&D waste recycling in Switzerland according to expert-based scenarios.

The introduction of LCA to C&D waste research is a step up from only viewing the impacts of final disposal of C&D waste. Life cycle thinking for C&D waste research provides a more comprehensive understanding of the impacts of C&D waste management, particularly methods to address waste (i.e. reuse, recycling, energy recovery and landfill). However, the development of a life cycle database for C&D waste is lacking, even in developed countries. This would limit the adoption of LCA in C&D waste research and further limit knowledge on the impacts of C&D waste.

2.4.4 Improving C&D waste management – from a management science perspective

A wide range of topics have been identified from the perspective of management science, with the ultimate aim of managing and minimising C&D waste. Each topic is discussed below.

2.4.4.1 Quantifying the generation of C&D waste

Waste generation has been a hot topic in C&D waste research over the past 20 years. These studies can be generally divided into three categories (i.e. surveying C&D waste generation in particular regions, investigating waste generation rates and estimating the generation amount of C&D waste through various models). A considerable number of studies were conducted to survey waste generation in specific countries/regions, such as the USA (Cochran et al., 2007), Norway (Bergsdal et al., 2007), Malaysia (Lau et al., 2008), Spain (Solis-Guzman et al., 2009), Portugal (Coelho & de Brito, 2011) and China (Wu et al., 2016a; Zheng et al., 2017). Data on estimating waste generation in such studies is mainly gathered through site interview, questionnaire, site visits, and observation methods.

Given the various types of construction projects inducing waste, the waste generation rate is regarded as a critical indicator to quantify the amount of C&D waste generated. The rationale for developing this indicator is that the average amount of waste generation in the same type of projects is normally a small variation (Li et al., 2013; Lu et al., 2011, 2017; Malia et al., 2013). As for the estimation of C&D waste via models, Kern et al. (2015) proposed a model to estimate C&D waste in high-rise buildings following a multiple regression model. Won et al. (2016) proposed an approach to estimate the amount of C&D waste avoided as a consequence of Building Information Modelling (BIM) oriented design. Wu et al. (2016b) developed a method to predict the amount of demolition waste at city level with the aid of the Geographic Information System (GIS). Although traditional methods (e.g. site interview, questionnaire, site visits, and observation) have been dominant approaches used in prior studies, new approaches have been developed in recent years.

2.4.4.2 C&D waste reduction via management measures

Waste reduction/minimisation is a fundamental goal of managing C&D waste. The C&D waste management situation in different countries has been investigated with a primary aim to divert wasted building materials from landfill, such as in the UK (Ajayi et al., 2016), Turkey (Esin & Cosgun, 2007), Malaysia (Begum et al., 2007) and China (Tam & Tam, 2008). Apart from concrete C&D waste reduction measures in design, construction, operation and demolition, human factors and economic incentives to reduce C&D waste have been discussed in prior studies:

- *Understanding human factors in C&D waste management.* Human factors in C&D waste management have attracted increased attention from scholars worldwide. This is because attitudes and behaviours of stakeholders can significantly affect the effectiveness of C&D waste management practice (Lu & Yuan, 2010). In the context of the Palestinian territory, Al-Sari et al. (2012) examined the potential impact of behaviours and attitudes on the performance of waste management. Udawatta et al. (2015b) investigated stakeholders' attitudes and behaviours toward waste management in Australia and consequently identified ways for improving waste management practice. Tam and Hao (2016) investigated attitudes of the Toronto construction industry towards recycling on construction sites. Wu et al. (2017) examined critical factors in contractor's behaviour in terms of managing C&D waste in mainland China. Yuan et al. (2018) identified factors influencing project managers' behavioural intentions to reduce waste in construction projects. All these studies confirmed the importance of human factors in affecting C&D waste management.
- *C&D waste disposal charging scheme.* The effectiveness of the C&D waste disposal charging scheme is regarded as critical in minimising waste generation at source. In Hong Kong, the disposal of C&D waste has emerged as a crucial problem because of limited land resources for C&D waste landfill as a destination of final disposal (Poon et al., 2013), which has resulted in serial studies examining the effectiveness and impacts of the C&D waste disposal charging scheme in the region (Hao et al., 2008; Yu et al., 2013). Recently this issue has attracted attention in Mainland China. For example, Yuan and Wang (2014) developed a system dynamics model to explore an appropriate waste disposal charging fee in Shenzhen in South China.

2.4.4.3 Economic feasibility of C&D waste recycling

C&D waste management, particularly recycling of C&D waste forms as an integral part of the circular economy. Several studies have examined the economic feasibility of C&D waste recycling, given that a primary drive for stakeholders to implement waste recycling lies in the economic benefits of waste recycling (Begum et al., 2006; Coelho & de Brito, 2013; Jung et al., 2015; Zhao et al., 2010). The findings from these studies showed that recycling of C&D is economically feasible and also plays an important role in improved environmental management (Begum et al., 2006). However, recycling costs are strongly influenced by transport distance, construction site conditions, and the amount of waste to be recycled (Jung et al., 2015). One of the difficulties in conducting valid studies to examine the feasibility of C&D waste recycling is defining the appropriate system boundary, as the different setting of the system boundary can change the results dramatically. The assumption made here is sometimes unrealistic in the real world, for instance, C&D waste materials cannot always be treated on time and recycled products cannot always be sold at targeted prices, which can influence economic feasibility evaluation.

2.4.5 Reducing C&D waste – from Architecture, Engineering, Construction and Operation of Buildings perspectives

As the generation of C&D waste is determined by design activities, construction, renovation, maintenance and demolition, some research efforts have emerged from the disciplines of Architecture, Engineering, Construction and Operation of Buildings (i.e. the disciplines that design, produce and manage buildings respectively).

2.4.5.1 C&D waste reduction from design

There are studies examining major factors that affect the minimisation of C&D waste reduction, by relating to certain project stages. It is a critical strategy to adopt waste minimisation design to minimise the generation of C&D waste, considering the detail of the construction project can prevent unnecessary design changes and over consumption of materials, the main factors that generate C&D waste (Osmani et al., 2008). Wang et al. (2014) identified critical enablers to effective waste minimisation during the design phase, particularly design changes. Although researchers are aware that design plays a critical role in affecting C&D waste generation, the concept of reducing C&D waste from design has not been widely used in prior studies. Architects, for example, did not view C&D waste issues as a priority in the design process (Osmani et al., 2008). This is mainly due to lack of an effective approach to evaluate the effect of waste minimisation design on reducing C&D waste generation (Wang et al., 2016). If the effect cannot be proven, it is difficult to convince architects to adopt specific design methods for reducing C&D waste. Hence, the value of reducing C&D waste by design is currently overlooked in the field.

2.4.5.2 Reducing C&D waste during construction, operation and demolition stages

The view is widely taken that C&D waste is mainly generated during construction and demolition stages. Significant attempts have been made to reduce C&D construction waste on site (Hao et al., 2008; Poon et al., 2001, 2004; Wang et al., 2010). Onsite sorting has been recognised as an effective way to reduce waste generation and increase reuse and recycling of C&D waste (Poon et al., 2001; Wang et al., 2010). More recently, renovation and maintenance of buildings have been identified as important sources of C&D waste, which also generates waste on a smaller scale compared to construction and demolition (Cheng & Ma, 2013; Lu et al., 2016). Although many recommendations to reduce C&D waste in prior studies have been proposed, one unavoidable problem is the lack of meaningful method to assess the effectiveness of waste management activities. If they prove useful, proposed waste reduction methods in prior studies can be adopted in practice.

2.5 Key research gaps in C&D waste management studies

Following critical analysis of developed theories and concepts of C&D waste research, preliminary achievements in selected samples were identified. Based on these achievements, strengths/weaknesses and knowledge gaps are analysed. By combining existing knowledge in the field and highlighting what has already been done, what has not been done, and how it can be done, some key research gaps emerging from this study are discussed below.

2.5.1 Expending the research boundary of C&D waste flows

As discussed in section 2.4, tracking the material flows of C&D waste is a significant study area, which is about understanding material flows from waste generation to final disposal. With this information, waste management measures can be applied to minimise waste generation and reduce waste being disposed of in landfill (Wu et al., 2019a). For instance, Hu et al. (2010) adopted a dynamic material flow approach to analyse C&D waste generated in the urban housing system in Beijing. Based on C&D waste material flow, environmental impacts can be evaluated. For instance, by investigating the C&D waste recycling chain in Italy, Blengini and Garbarino (2010) analysed the energy and environmental implications in the industry. The material flows of C&D waste are sometimes integrated with other supply chains and during the planning process of the management system, the dynamics of waste flow should be taken into account when determining C&D waste recycling networks (Hiete et al., 2011). Although many studies regarding C&D waste generation and flow can be sourced in Europe, Asia and America, there is no related study of Oceania sourced in international journals. Hence, investigations of C&D waste generation in Australia can redress this gap in the area.

Several studies tracked the mass flow or material flow of C&D waste, and assessed the life cycle energy and resource efficiency of C&D waste (Blengini & Garbarino 2010; Hiete et al. 2011; Huang & Hsu 2003; Wiedenhofer et al. 2015), but they mainly focus on C&D waste materials such as concrete, brick and mortar, because they are 70-80% of the total mass of generated C&D waste (Zheng et al., 2017). Apart from these materials, C&D waste consists of numerous valuable materials including wood, glass, metals and plastics. Mixed C&D waste may contain hazardous components (e.g. asbestos) that severely impact human health, the natural environment and society (Gualtieri, 2013; Roussat et al., 2008). These small fractions of C&D waste were normally overlooked in most waste management systems, mainly because they only contribute a few portion of total weight and they are difficult to be sorted out from mixed waste. To better understand the character of C&D waste flows, extending the research boundary to understand how multiple C&D waste flows from generation to final disposal is worthy of further investigation.

2.5.2 Understanding cross-regional mobility in C&D waste management

Since a large amount of C&D waste is contributed by materials that are heavy and of low value, the transportation of waste is normally of low-level efficiency (Coelho & de Brito, 2011; Miatto et al., 2017; Solis-Guzman et al., 2009). C&D waste is generally managed by local authorities in some countries. Such waste is normally treated and recycled at local recycling facilities or disposed of in local landfill (Miatto et al., 2017; Stephan & Athanassiadis, 2018; Wiedenhofer et al., 2015). Therefore, the management of C&D waste is usually viewed as local-closed issues, and the system boundary has been limited at regional level (Wu et al., 2019b). Driven by various factors such as facility availability, regulations, economic incentive and common industry practice, it has been reported that C&D waste was transported from the originally generated region to other regions for further treatment in some countries (Dee, 2018; GISA, 2019; NSW EPA, 2019; QG, 2018; SV, 2017). For example, a large amount of C&D waste has been transported cross-border in eastern regions in Australia for landfill, in response to significant differences in recycling and disposal costs among regions (Dee, 2018). Academic institutions in China are promoting cross-regional mobility of C&D waste in the Greater Bay Area (HKU, 2019). Such cross-regional mobility will affect the quantity of waste in regional waste management systems, which will further affect environmental, economic and social performance of the system (SV, 2017). Therefore, it is necessary to rethink the system boundary of C&D waste management and investigate cross-regional mobility of C&D waste. This will help to better understand the drivers to optimise waste management systems for improving management efficiency. However, very few studies have attempted to examine cross-regional mobility issues in C&D waste management.

2.5.3 Developing advanced performance assessment methods for C&D waste management

One of the purposes of managing C&D waste is to achieve sustainability in the construction industry (Blengini, 2009) and recycling C&D waste is viewed as an essential part of the circular economy. As a result, attempts have been made to assess C&D waste management performance from different perspectives by employing various models (Ajayi et al., 2015; Saez et al., 2013; Tam, 2008). For instance, some studies developed their sustainability assessment model to assess C&D waste management performance, mostly focusing on economic feasibility which has been a main concern of project stakeholders (Begum et al., 2006; Jung et al., 2015; Zhao et al., 2010). Some studies have investigated C&D waste management performance from a holistic view by simultaneously covering economic (Ye et al., 2012; Zhao et al., 2011), environmental (Ding et al., 2016; Marzouk & Azab, 2014) and social (Yuan, 2012) aspects. In these studies, C&D waste management systems can be defined at different levels (i.e. project and regional levels). Some studies have assessed different C&D waste management activities during the life cycle, particularly from an environmental perspective (Butera et al., 2015; Mercante et al., 2012; Ortiz et al., 2010; Penteado & Rosado, 2016; Wang et al., 2018).

In these studies, C&D waste is viewed from different perspectives, for example, products, processes, or systems; however, as all these previous studies viewed the management of C&D waste as a local-closed issue, the researchers did not consider particular parameters for cross-regional mobility in C&D waste management when evaluation criteria were developed. It is difficult to determine whether a C&D waste management system is effective if only one dimension (e.g. economic) performs well while other dimensions perform insufficiently. By examining existing studies, a lack of a systematic performance assessment approach for evaluating the effectiveness of C&D waste management regarding environmental, economic and social aspects is evident. Therefore, the impacts assessment methodology for cross-regional mobility of C&D waste management could make a contribution to management performance assessment methodologies for C&D waste.

2.6 Summary

This chapter presented the literature review of C&D waste and related management issues, and then identified some research gaps. A bibliometric analysis and in-depth contents review were conducted.

Firstly, a comprehensive bibliometric analysis was conducted to review C&D waste articles published in the WoS database; 1027 C&D waste articles published from 1994 to 2017 were reviewed and analysed. Results showed that C&D waste had attracted increasing research efforts over the past three decades where the number of C&D waste articles increased eight times. By measuring the main authors' contributions, it has been found that researchers from China, Spain and Brazil contributed a large number of publications. This reveals a geographical evolution of C&D waste research from developed regions to developing regions within the last ten years. This study describes the social networks among the authors, countries and organisations. Results showed that China, England, the USA and Australia are quite active in building a cooperative network with scholars from other regions.

Secondly, by conducting an in-depth contents review, this study examined C&D waste-related articles in order to identify key research gaps in C&D waste management study. Results showed that current C&D waste research has been carried out from various perspectives. These mainly include Environmental Science and Environmental Engineering, Material Science and Engineering, Industrial Ecology, Management Science, and Architecture, Engineering, Construction and Operation of Buildings. By combining existing knowledge in the field and highlighting what has been done, what has not been done, and how it can be done, some key research gaps that led to this study were identified and discussed.

Chapter 3. Literature review: Part 2

3.1 Introduction

As discussed in Chapter 2, significant efforts have been made to assess C&D waste management performance regarding the impacts of C&D waste management activities, though studies were conducted from different perspectives by employing various models. However, no study has attempted to provide the big picture by systematically examining major methods, models and outcomes in current studies. This oversight limits further application of developed methods and models to improve C&D waste management practices.

This chapter aims to gain an in-depth understanding of studies on impacts of C&D waste management activities and to provide a theoretical base for this study. Based on an in-depth review of 36 selected papers (see Table A-3.1 in Appendix B), the chapter discusses three main impact assessment approaches, namely sustainability based methods (section 3.2), system thinking based methods (section 3.3), and life cycle thinking based methods (section 3.4). This chapter summarises the main assessment approaches, concerning research methods, data collection methods and critical indicators for assessment (section 3.5). A general research procedure for assessing impacts of C&D waste management is also proposed (section 3.6).

The contents of this chapter have been published in associated publication 3 listed on page xiii. The contents merit existing literature from multiple aspects. Firstly, given the fact that reasonable waste management performance assessment is an important aspect to develop a robust waste management system, an in-depth review is crucial in developing assessment models and more robust methods. Secondly, a well-developed framework can be useful for researchers looking to assess C&D waste management performance. Finally, review-based contents can also be valuable for practitioners and policy makers to improve practice, based on a comprehensive understanding of the significance and complexity of environmental, economic and social impacts of C&D waste management.

3.2 Sustainability based assessment methods

Sustainability assessment is a hot topic in C&D waste research. These studies are named using keywords such as sustainability (environmental, economic and social performance), economic feasibility and management effectiveness.

3.2.1 Sustainability: Economic, environmental and social performance

A significant number of prior studies are defined within the framework of sustainability (i.e. economic, environmental and social sustainability). Some studies developed their sustainability assessment model to assess C&D waste management performance. In terms of the selection of research priorities, different studies favour different strategies. Some studies developed multi-criteria assessment models covering more than one aspect amongst economic, environmental and social issues (Klang et al., 2003; Kucukvar et al., 2016; Marrero et al., 2017). For instance, Klang et al. (2003) presented a model for evaluating waste management systems and their contribution to sustainable development, covering environmental, economic and social aspects. The model was tested in cases in Norway and Sweden regarding recovery and recycling of C&D waste. While some studies concentrated on only one aspect, for example, economic (Srour et al., 2013; Stenis, 2005; Wang et al., 2004;), environmental (Butera et al., 2015; Dejkovski, 2016; Ding et al., 2016; Roussat et al., 2009) or social (Yuan, 2012) aspects.

Although the priority for these studies differed, they shared some common research procedures. Usually, the first step is to define the research goal and scope. The second step is to identify the criteria. The selection of criteria is generally via a literature review according to the study purpose. The third step is to quantify the indicators. The final step is to run the model (i.e. calculation), and usually this is based on scenario analysis. Developed models are typically adopted in a case study to validate the proposed model. In most cases, the study would provide quantitative results, while sometimes resulting in qualitative recommendations (Yuan, 2013).

3.2.2 Economic feasibility-focused research

In fast developing countries such as China, there are huge demands on C&D waste disposal, and there is a vast market potential for recycled C&D waste products. The recycling of C&D waste is seen as a market activity (Wu et al., 2015). Economic feasibility is frequently mentioned in assessing C&D waste management performance because it has been a major concern of project stakeholders (Yuan et al., 2018). Many studies have indicated that C&D waste strategies such as waste minimisation, onsite recycling and centralised recycling would have economic benefits, and these methods are generally feasible. For instance, Begum et al.

(2006) found that waste minimisation is economically feasible by performing a benefit-cost analysis. However, many studies also indicated that economic feasibility of C&D waste recycling would depend on various factors, such as economies of scale and methods of recycling. Duran et al. (2006) suggested that economic viability is likely to occur when the cost of landfill exceeds the cost of bringing the waste to the recycling centre and the cost of using primary aggregates exceeds the cost of using recycled aggregates. This is mainly because economies of scale imply that an increase in size of a recycling centre, in turn, results in a decrease in recycling costs. Moreover, Jung et al. (2015) evaluated the economic feasibility of two recycling processes: onsite recycling and a private recycling centre. The results show that recycling costs were strongly influenced by transport distance, construction site conditions, and the amount of waste concrete recycled. Hence, the results of economic feasibility assessment might vary under different circumstances.

On the other hand, to enhance economic viability of C&D waste recycling, some scholars also provided recommendations from various aspects. For instance, Zhao et al. (2010) suggested that economic instruments such as tax can be adopted in C&D waste to balance economic viability of C&D waste recycling. Furthermore, economic instruments for minimising construction waste can be adopted to promote revenue for environmental policy, encourage waste prevention efforts, discourage least desirable disposal practices, and avoid negative consequences of environmentally unfriendly treatment and disposal practices Begum et al. (2006). Of concern is that the effectiveness of policies for improving economic performance of C&D waste can hardly be validated.

3.2.3 Management effectiveness-focused research

How to assess the effectiveness of C&D waste management is another hot topic in the field, although the definition is yet to be agreed upon. The management of effectiveness-focused research mainly targets the development of concept and indicators to assess management effectiveness at different levels. Typically, at the project level, Saez et al. (2013) evaluated the effectiveness of 20 best practice measures regarding C&D waste management, namely the use of industrialised systems, contract of suppliers managing waste, and distributing small containers among work areas. At the city level, Tam (2008) investigated the effectiveness of existing waste management methods in the Hong Kong construction industry. This study identified the main benefits gained, significant difficulties and some useful measures to encourage waste management. Yuan (2013) proposed a framework for assessing the effectiveness of C&D waste management. This study identified 30 key indicators affecting the overall effectiveness of C&D waste management from a holistic perspective and further developed an effective framework for assessing C&D waste management by integrating identified indicators. At industry level, Ajayi et al. (2015) explored factors impeding the effectiveness of existing waste management strategies, as well as plans for reducing waste in the construction industry. With these achievements in prior exploratory studies, more efforts is needed to expand existing research on assessing the effectiveness of C&D waste management in future.

3.3 System thinking based assessment methods

System thinking is a holistic analysis approach capable of explaining how a system's constituent parts interrelate, and how systems work over time and within the context of larger systems. System dynamics (SD), introduced by Jay Forrester in the 1960s, provides useful tools for better understanding large-scale complex management problems in line with system thinking principles (Yuan, 2012). SD has been a well-established methodology for understanding, studying, visualising and analysing complex dynamic feedback systems. Usually SD requires constructing "causal loop diagrams" or "stock and flow diagrams" to form a quantitative model for applications (Dyson & Chang, 2005). There are a number of studies employing SD to assess C&D waste management performance (Ding et al., 2016; Marzouk & Azab, 2014; Tam et al., 2014; Ye et al., 2012; Yuan, 2012; Zhao et al., 2011). In the above mentioned applications, five phases, namely problem definition, dynamic hypothesis, simulation model, model testing and policy design are commonly designed.

(1) Problem definition

The first step is to define the research goal and scope (Yuan, 2012). To optimise C&D waste management, previous studies developed SD models to evaluate C&D waste management performance by integrating economic, environmental and social aspects. The C&D waste system can be defined either at project level or regional level. At project level, Zhao et al. (2011) evaluated the economic feasibility of choosing C&D waste recycling centres in Chongqing, China. Ye et al. (2012) developed an SD model to assess environmental performance of C&D waste management and a new frame-structured building in Shenzhen City, China was chosen as the case study. Yuan (2012) developed an SD model to assess the social performance of C&D waste management. At the city level, Tam et al. (2014) developed an SD model for C&D waste management in China. It examined how landfill charges would affect illegal dumping behaviours. Ding et al. (2016) examined how changes in sorting behaviours and source reduction measures would influence C&D waste reduction performance. At the national level, Marzouk and Azab (2014) evaluated the impacts of recycling and landfill disposal for C&D waste in Egypt.

(2) Dynamic hypothesis

In this step, variables and relationships among variables were structured by a causal loop diagram. The interactions among different variables and loops decide the system's behaviour (Marzouk & Azab, 2014). The identification of variables and variable relationships are confirmed based on literature review (Marzouk & Azab, 2014), interview or mixed methods including the above mentioned methods (Ding et al., 2016). An example of a causal loop diagram for evaluating social performance of C&D waste management is illustrated in Figure 3.1 (Yuan, 2012).

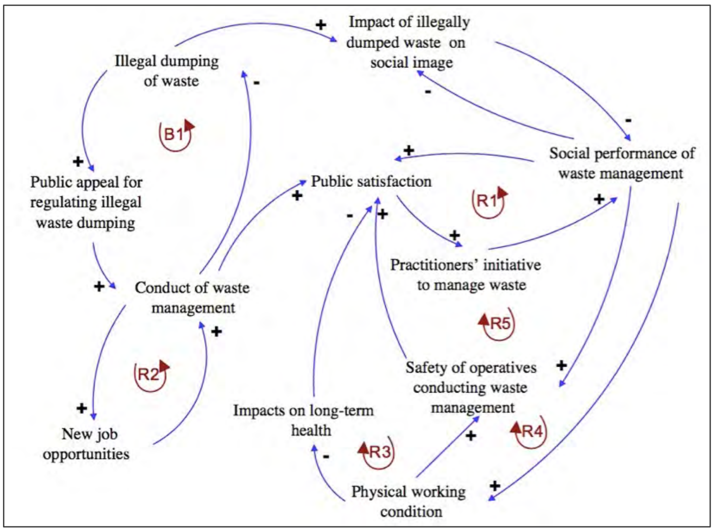


Figure 3.1: Causal loop diagram for evaluating C&D waste management performance

(Source: Yuan, 2012)

(3) Simulation model

In this stage, variables and relationships in the causal loop diagram are quantified and together form the stock and flow diagrams, used to quantify system structure and behaviour. The valuation of variables is generally based on multiple methods, including theoretical assumption, experts' estimation and secondary data (Yuan, 2012). Equations are used to express the interactions among variables in the model.

(4) Model testing

Once initial models have been estimated, a series of model tests are conducted to build model confidence. Examination of the SD model normally includes five aspects, namely boundary-adequacy test, structure verification tests, dimension consistency test, parameter verification test and extreme conditions test (Qudrat-Ullah & Seong, 2010). Despite this, validation of the SD model is controversial in many discussions due to the nature of the methodology. Hence, the reliability of SD models largely depends on modelling capacity and skills of the researchers.

(5) Policy design

Based on the well-established SD model, scenario analysis can be conducted to simulate the model and to develop practical implications further. This analysis usually includes single-policy scenarios and multi-policy scenarios. For instance, the changing of the physical working environment and operatives' safety is adopted to simulate the influence on the value of social performance of C&D waste separately and collaboratively in a prior study (Yuan, 2012).

Although there are a number of studies employing SD to assess C&D waste management performance, the validation of the SD model was controversial in many discussions due to the nature of the methodology. Meanwhile, Although SD has the ability to combine economic, environmental and social impacts in a single model, and also include the influence of the passage of time on the outcomes, it is not able to quantify the accurate environmental, economic and social impacts for various scenarios. Due to these limitations, SD is not selected as the main method to quantify the impacts of cross-regional mobility of C&D waste in Australia in this study.

3.4 Life cycle thinking based assessment methods

Life cycle thinking is a widely adopted approach to assess the impacts of C&D waste management, particularly environmental performance of a product or system. It considers the environmental impacts of a product system 'from the cradle to the grave', which examines life cycle stages from raw material extraction, manufacturing, transportation, to use and end-of-life treatment and final disposal (McDougall et al., 2008). Based on the contribution by the Society for Environmental Toxicology and Chemistry (SETAC), the International Standards Organisation (ISO) has further developed the ISO 14040 series on Life Cycle Assessment (LCA). According to ISO 14040, the phases of an LCA consist of four stages, namely goal and scope definition, inventory analysis, impact assessment and interpretation (Finkbeiner et al., 2006). However, the ISO standards are defined in a rather vague language, which makes it difficult to assess whether an LCA has been made according to the standard.

LCA has also been applied to quantify and compare potential environmental impacts related to recovery, utilisation and final disposal of C&D waste materials (Butera et al., 2015). There are a number of studies employing LCA or combining other tools with LCA for more extensive C&D waste management assessments (Bohne et al., 2008; Chau et al., 2017; Kucukvar et al., 2016; Mercante et al., 2012; Ortiz et al., 2010; Penteado & Rosado, 2016; Simion et al., 2013; Wang et al., 2018; Wu et al., 2015). These studies followed the fundamental structure of LCA provided by ISO 14040 series. Although these phases vary in different cases, this structure is the basis of all LCA studies. The following contents will showcase how LCA is adopted in C&D waste management.

(1) Goal and scope definition

The most critical methodological choices, assumptions and limitations should be clearly described in the first phase. These include the functional unit, initial system boundaries and criteria for inclusion of inputs and outputs, and dealing with the multifunctional process (Goedkoop et al., 2008). A workable detailed illustration for this can be found in the Introduction to LCA with *SimaPro* software. It is found that almost all previous LCA-C&D waste studies chose 1 t of C&D waste consisting of various waste fractions as the functional unit, which is reasonable due to the nature of C&D waste.

In C&D waste related studies, the setting of the system boundary can be summarised according to the following categories (from micro scale to macro scale):

(a) The C&D waste management of a project. For example, Ortiz et al. (2010) evaluated environmental impacts of the treatment of construction waste generated from the LIFE 98 ENV/E351 project. Chau et al. (2017) conducted a study on the life cycle energy assessment (LCEA) of the end-of-life phase of a high-rise concrete office building in Hong Kong. A typical high-rise residential building in China was selected as the study case (Wang et al., 2018).

(b) The overall C&D waste management system in a city. For example, Bohne et al. (2008) evaluated the eco-efficiency of a C&D waste recycling system at the city level in

Norway; Wu et al. (2015) examined the carbon emission of handling construction waste in China.

(c) The recycling facility for overall C&D waste in a country. For example, Mercante et al. (2012) compared the environmental performance for two types of C&D waste recycling facilities in Spain. A similar study was carried out based in Brazil (Penteado & Rosado, 2016).

(2) Scenario setting

Scenario analysis is employed to determine optimal C&D waste management scenarios. There are two categories that set up scenarios in previous C&D waste LCA studies, which compare: (a) current practice situations, targets in the C&D waste management plan, ideal prospects (i.e. maximum recycling, maximum energy recovery) and worse case (i.e. landfill) (Bohne et al., 2008; Chau et al., 2017; Ortiz et al., 2010; Wu et al., 2015); and (b) compare different treatment facility/systems. For instance, Mercante et al. (2012) compared the performance between a small-scale mixed C&D waste sorting facility and larger-scale C&D waste recycling centre. Similar scenario settings were adopted in other studies (Dahlbo et al., 2015; Penteado & Rosado, 2016). Wang et al. (2018) compared factory C&D waste recycling with mobile onsite C&D waste recycling. Scenario analysis helps to determine the more suitable C&D waste management method and to make strategic recommendations to decision makers for enhancing C&D waste management performance as a whole.

(3) Inventory analysis

The most demanding task in performing an LCA is data collection. Although much secondary data is available in the literature or in databases such as *Ecoinvent*, it is usually found that at least a few processes or materials are unavailable (Goedkoop et al., 2008). Therefore, a systematic data collection plan is helpful to establish the inventory (Dahlbo et al., 2015; Penteado & Rosado, 2016). Previous studies have developed some strategies to collect data. Regarding the foreground data used to create the modelling system, it is normally collected from specific companies via interview or questionnaire. Since these data may involve confidentiality issues and terminology issues, the willingness to provide such data sometimes depends on the relationship between the researchers and data owners. For instance, to collect data, Penteado and Rosado (2016) not only conducted site visits on recycling projects, but organised regular meetings with technicians from C&D waste management departments in the municipality. In terms of background data on the production of generic materials, energy, transport and waste management, this is usually available in databases or can be found in the literature. In most cases, an extensive literature review was essential to capture missing data not in the database (Dahlbo et al., 2015). The most welcome data sources for background data in C&D waste LCA studies is the *Ecoinvent* database, which has been adopted by several studies (Bohne et al., 2008; Mercante et al., 2012; Ortiz et al., 2010; Wang et al., 2018; Wu et al., 2015).

(4) Impact assessment

According to ISO 14040/44, life cycle impact assessment is designed to understand and evaluate the magnitude and significance of potential environmental impacts of the system. It usually contains essential elements (i.e. classification and characterisation) and optional elements (i.e. normalisation, ranking, grouping and weighting) (Finkbeiner et al., 2006). Previous C&D waste LCA studies usually select one well-developed impact assessment method or a refined method, rather than create impact assessment methodologies. For instance, Bohne et al. (2008) chose the Eco-Indicator 99 method, because it is a single value indicator and easy to communicate results to decision makers. Wang et al. (2018) adopted the IPCC 2013 GWP 100a V1.01 to calculate carbon emissions of raw material substitutes in their study. As distinct from most studies, Butera et al. (2015) employed *EASETECH*, a model for LCA of waste and energy systems developed by the Technical University of Denmark. In order to suit the characterisation of C&D waste, Ortiz et al. (2010) added other eco-efficiency indicators, such as resources use, renewable energy, non-renewable energy and overall water use, into their refined method, based on the CML 2 baseline 2000 methodology for evaluation of the environmental profile.

In contrast, Penteado and Rosado (2016) excluded possible leachate emissions in soil and water, the impact categories of human toxicity, aquatic and terrestrial ecotoxicity from the CML 2 baseline 2001 methodology. Since some studies only focused on a single issue, such as energy saving (Chau et al., 2017) or carbon emissions (Wu et al., 2015), they used so-called single-issue methods, which is relatively robust and easy to use. However, it is evident that single-issue methods do not comply with ISO 14044 as this standard requires a thoughtful assessment of all relevant impact categories (Goedkoop et al., 2008). It is not easy to determine the optimal method, as these methods are developed by different research teams around the globe.

As discussed above, LCA is a suitable method to quantify the environmental impacts and life cycle thinking is also an excellent theoretical base for conducting impacts assessment respect to economic and social aspects. These advantages of LCA are suitable to address research objectives of this study. Therefore, LCA is selected as the main method to quantify the impacts of cross-regional mobility of C&D waste in Australia in this study.

3.5 Critical indicators for impacts assessment of C&D waste management

Previous studies mainly focus on environmental, economic and social performance of C&D waste management. Some studies may choose one or two performance categories while others conduct a comprehensive assessment covering all three aspects. Table 3.1 lists the primary studies on C&D waste management performance assessment. The results show that compared to environmental and economic aspects, social aspects attracted less attention, even though social impacts have been highlighted in some studies (Chung et al., 2003; Klang et al., 2003; Manowong et al., 2012; Yuan, 2012, 2013).

Table 3.1: Performance assessment aspects of prior C&D waste studies

	Publications	Keywords	Environmental	Economic	Social
1	Chung and Lo, (2003)	Sustainability	√	√	√
2	Klang et al., (2003)	Sustainability	√	√	√
3	Begum et al., (2006)	Economic feasibility		√	
4	Duran et al., (2006)	Economic viability		√	
5	Bohne et al., (2008)	Eco-efficiency	√	√	
6	Gomes et al., (2008)	N/A	√	√	
7	Rocha & Sattler, (2009)	N/A		√	
8	Lu et al., (2009)	Cost efficiency		√	
9	Roussat et al., (2009)	Sustainability	√		
10	Shen et al., (2009)	Benefits		√	
11	Merino et al., (2010)	Sustainability	√		
12	Ortiz et al., (2010)	Environmental performance	√		
13	Tam et al., (2010)	Benefits/Difficulties/Recom mendation	√	√	
14	Zhao et al., (2010)	Economic feasibility		√	
15	Yuan et al., (2011)	Emergy analysis (efficiency)	√	√	
16	Zhao et al., (2011)	Economic feasibility		√	
17	Manowong, (2012)	Sustainability	√	√	√
18	Mercante et al., (2012)	Environmental performance	√		
19	Ye et al., (2012)	Environmental performance	√		
20	Yuan, (2012)	Social performance			√
21	Simion et al., (2013)	Sustainability/Ecological footprint	√		
22	Srour et al., (2013)	Economic feasibility		√	
23	Yuan, (2013)	Effectiveness	√	√	√
24	Marzouk & Azab, (2014)	Environmental and economic impact assessment	√	√	
25	Tam et al., (2014)	Land occupation	√	√	
26	Butera et al., (2015)	Life cycle assessment	√		
27	Dahlbo et al., (2015)	Environmental performance and economic performance	√	√	
28	Dejkovski, (2016)	Environmental performance	√		
29	Ding et al., (2016)	Environmental impacts	√		
30	Ding et al., (2016)	Environmental performance	√	√	
31	Kucukvar et al., (2016)	Life cycle assessment	√	√	
32	Penteado & Rosado, (2016)	Life cycle assessment	√		
33	Zambrana-Vasquez et al., (2016)	Environmental performance	√		
34	Chau et al., (2017)	Environmental performance	√		
35	Marrero et al., (2017)	Ecological footprint and economic impact	√		
36	Wang et al., (2018)	BIM; LCA	√		

3.5.1 Indicators for environmental impacts assessment

Although the goals for assessing environmental impacts of C&D waste can be similar, the selection of methods and indicators varies among different studies, which is discussed next.

3.5.1.1 Using a well-developed method for environmental impact assessment

In terms of LCA studies, most studies did not create their impact assessment methodologies; instead, they chose to select a sophisticated method for assessment (Bohne et al., 2008; Butera et al., 2015; Penteado & Rosado, 2016). Regarding the LCA, such impact assessment methods can be found in software such as *SimaPro, GaBi, etc*. These methods are developed by various research teams and subsequently used around the globe, though there has been no consensus yet on the 'best method.' As a result, most LCA practitioners seem to choose a method by popularity, or worse, adopting a default method integrated with the software used. Besides, instead of selecting one general method, some experts may select individual impact categories such as carbon emission and energy consumption (Chau et al., 2017; Wang et al., 2018). Table 3.2 summarises some popular methods (original versions), selected from the *SimaPro Database Manual – Methods Library.* These methods may have updated versions.

Table 3.2: Some popular environmental impact assessment methods

(Source: *SimaPro Database Manual – Methods Library*)

No.	Method	Developer	Notes	Application
1	CML-IA	Center of Environmental Science of Leiden University	The impact assessment method implemented as CML-IA methodology is defined for the midpoint approach. Normalisation is provided but there is neither weighting nor addition.	Zamagni, et al., (2012)
2	Ecological scarcity 2013	Swiss Federal Office for the Environment (FOEN)	In specific cases, global, international or regional goals are used and converted to the Swiss level.	Frischknecht et al., (2015)
3	EDIP 2003	Institute for Product Development (IPU) at the Technical University of Denmark	The main innovation of EDIP2003 lies in the consistent attempt to include exposure in the characterization modelling of the main non-global impact categories. EDIP2003 can originally be used both with and without spatial differentiation.	Godskesen et al., (2012.)
4	EPD 2013	Swedish Environmental Management Council (SEMC)	All impact categories are taken directly from the CML-IA baseline method (eutrophication, global warming and photochemical oxidation) and CML-IA non baseline method (acidification)	Moraes et al., (2013)
5	EPS 2000	Centre for Environmental Assessment of Products and Material Systems. Chalmers University of Technology	The EPS system is mainly aimed to be a tool for a company's internal product development process.	Steen (1999)
6	Impact 2002+	Swiss Federal Institute of Technology - Lausanne (EPFL)	The characterization factors for human toxicity and aquatic and terrestrial ecotoxicity are taken from the methodology IMPACT 2002+. The characterization factors for other categories are adapted from existing characterizing methods, i.e. Eco-indicator 99, CML 2001, IPCC and the Cumulative Energy Demand.	Jolliet et al., (2003)

7	ReCiPe	1) PRé Consultants, Amersfoort, Netherlands 2) CML, University of Leiden, Netherlands 3) RUN, Radboud University Nijmegen Netherlands 4) RIVM, Bilthoven, Netherlands	ReCiPe is the successor of the methods Eco-indicator 99 and CML-IA. The purpose at the start of the development was to integrate the 'problem oriented approach' of CML-IA and the 'damage oriented approach' of Eco-indicator 99.	Goedkoop et al., (2008)
8	BEES	National Institute of Standards and Technology (NIST)	BEES is the acronym for Building for Environmental and Economic Sustainability, a software tool developed by the National Institute of Standards and Technology (NIST). BEES combines a partial life cycle assessment and life cycle cost for building and construction materials into one tool. BEES uses the SETAC method of classification and characterisation.	Lippiatt, (2000)
9	TRACI 2.1	US Environmental Protection Agency	The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), a stand-alone computer program developed by the United States.	Ryberg et al., (2014)
10	Cumulative Energy Demand (CED)	Ecoinvent version 1.01	The method to calculate Cumulative Energy Demand (CED) is based on the method published by Ecoinvent version 1.01 and expanded by PRé for energy resources available in the SimaPro database.	Frischknecht et al., (2007)
11	Ecological footprint	The University of British Columbia	The ecological footprint is defined as the biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption.	Wackernagel, (1994)

12	Ecosystem Damage Potential	Swiss Federal Institute of Technology (ETH)	The Ecosystem Damage Potential (EDP) is a life cycle impact assessment methodology for the characterization of land occupation and transformation.	Koellner et al., (2007)
13	GHG Protocol	World Resources Institute and the World Business Council for Sustainable Development	The Greenhouse Gas Protocol (GHG Protocol) is an accounting standard of greenhouse gas emissions.	García & Freire, (2014)
14	IPCC 2013	International Panel on Climate Change	IPCC 2013 is an update of the method IPCC 2007 developed by the International Panel on Climate Change. This method lists the climate change factors of IPCC with a timeframe of 20, 100 and 500 years.	Stocker et al., (2013)
14	Eco-indicator 99	PRé. Consultants	The Eco-indicator 99 focuses on the interpretation of results and uses the endpoint approach.	Goedkoop & Spriensma, (1999)

3.5.1.2 Refining a method for environmental impacts assessment

Although impacts assessment methods become very extensive and include more and more substances, they still do not cover all elements essential for comprehensive environmental assessment. This can be a methodological issue, because some methods, for example, do not include raw materials as an impact category. Therefore, some studies refined the impacts assessment method according to their research need. For instance, Ortiz et al. (2010) had to add four additional indicators including resources use, renewable energy, non-renewable energy and overall waste use in their model based on the CML 2 model.

3.5.1.3 Creating an original model involving performance assessment indicators

Compared to the LCA, SD studies have not developed comprehensive environmental impacts assessment methods. Those studies usually developed original models with performance assessment indicators derived from literature review, case study, or interview (Ding et al., 2016; Marzouk & Azab, 2014; Ye et al., 2012; Yuan, 2013). Besides, there are some other approaches adopted in assessing environmental performance (Marrero et al., 2017). These indicators mainly consider environmental components concerning air, water, raw material resource, energy, land and noise. The choice of indicators is mostly dependent on the goal and scope of studies.

Table 3.3: Environmental impacts assessment methods and indicators in C&D waste studies (Life cycle thinking)

Authors	Bohne et al., (2008)	Ortiz et al., (2010)	Butera et al., (2015)	Penteado & Rosado, (2016)	Chau et al., (2017)	Wang et al., (2018)
Method	LCA	LCA	LCA	LCA	Life cycle energy assessment	LCA
indicators source	Eco-Indicator 99[a]	CML 2 (baseline 2000)[b]	EASETECH[c]	CML 2 (baseline 2001) [b]	N/A	IPCC 2013 GWP 100a V1.01[d]
Indicators	Damage to resources	Acidification potential	Global warming	Acidification potential	Energy saving	Carbon emissions
	Damage to ecosystems	Global warming potential	Photochemical ozone formation	Global warming potential		
	Damage to human health	Eutrophication	Particulate matter	Eutrophication potential		
		Freshwater aquatic eco toxicity	Terrestrial acidification	Photochemical oxidation		
		Human toxicity	Freshwater eutrophication	Depletion of abiotic resources		
		Terrestrial eco toxicity	Marine eutrophication			
		Additional: Resources use Renewable energy Non-renewable energy Overall water use	Terrestrial eutrophication			
			…			

Note:

a. Eco-indicator 98 is based on inventory data from the *Ecoinvent* library and the USA Input Output Database 98;
b. CML is an impact assessment method proposed by Centre of Environmental Science of Leiden University;
c. EASETECH is a model for LCA of waste and energy systems developed by the Technical University of Denmark; and
d. IPCC 100 is a characterisation model developed by the Intergovernmental Panel on Climate Change for Climate change

Table 3.4: Environmental impacts assessment indicators in C&D waste studies (System thinking)

Authors	Ye et al., (2012)	Yuan (2012)	Marzouk & Azab, (2014)	Ding et al., (2016)
Method	SD	SD	SD	SD
Indicators source	Case study/literature review	Literature review/interview	Case study	Literature review/interview
Indicators	Air pollution	Land occupation due to waste landfill	NO_X emissions	Land Resource Index
	Illegally dumping on public living environment	Water pollution	GWP emissions	Water Resource Index
	Noise emission	Noise emission	Energy consumption	Energy Resource Index
	Water quality	Air pollution	Unit land loss by C&D waste landfilling	Air Resource Index
		Environmental impacts of illegal waste dumping on public living environment		

Table 3.5: Environmental impacts assessment indicators in C&D waste studies (Sustainability based thinking)

Authors	Gomes et al., (2008)	Manowong (2012)	Marrero et al., (2017)	Klang et al., (2003)	Roussat et al., (2009)	Merino et al., (2010)	Tam et al., (2010)
Method	Multiple criteria decision making	Structural equation modelling	work breakdown system	Original model	Original model	Original model	Original model
Indicators	CO_2 emissions	Waste generation	Energy	Energy consumption avoided	Energy resource conservation	Natural resource	Reducing the need for new landfill
		Air quality	Waste	Carbon dioxide equivalents saved	Material resource conservation	Air quality	Saving natural materials
		Water quality	Land	Potential acidification avoided		Water quality	
		Resource consumption	Water			Energy	
		Land degradation	Food consumption				
		Energy consumption					

3.5.2 Indicators for economic impacts assessment

Economic aspect has also attracted significant attention in previous studies. The economic impacts assessment of C&D waste mainly focuses on the cost aspect, and only a few studies take the benefit of revenue into consideration (Begum et al., 2006; Manowong, 2012; Zhao et al., 2011). The calculations of C&D waste handling costs were considered differently in different studies. For instance, some studies divide the cost according to the procedure of processing C&D waste, such as collection, transportation, landfilling, recycling and so on (Begum et al., 2006; Duran et al., 2006; Tam et al., 2014); some studies consider the cost of input resources, such as labour, energy, equipment, land and so on (Klang et al., 2003; Srour et al., 2013; Zhao et al., 2010)while some studies use more abstractive indicators such as investments, operational costs, treatment/disposal costs, taxes and subsidies (Bohne et al., 2008; Gomes et al., 2008; Zhao et al., 2011). Table 3.6 summarises the methods and indicators used for assessing economic performance of C&D waste management.

It is found that unlike environmental impacts assessment, there are not many well-developed methods for economic impacts assessment. Although the possibility of adding economic issues to the LCA methodology has been discussed among studies such as the Life Cycle Cost Assessment, often these debates are confused and not productive (Goedkoop et al., 2008). There are numerous difficulties in accurately assessing economic performance of C&D waste management. Firstly, vital cost factors such as investment, research, overheads and marketing are usually not modelled, or at least underrepresented in a well-developed model such as the LCA model. Secondly, previous models do not have a time perspective, which makes it challenging to model interest or discount rates. Also, precision requirements for cost and revenue calculations are high. An error in the computation of a sales margin of a few percent can be disastrous for a company. Many companies, therefore, input human resources to keep track of market prices, exchange rates and sales margins. It is not realistic to assume that an LCA expert can make an improvement. And last but not least, the economic data usually are confidential commercial information for companies, making it difficult to obtain such data from public sources or through interviewing C&D waste management practitioners (Goedkoop et al., 2008).

Table 3.6: Indicators for economic impacts assessment

Authors	Klang et al., (2003)	Begum et al., (2006)	Duran et al., (2006)	Bohne et al., (2008)	Gomes et al., (2008)
Method	Original model	Original model	Original model	LCA	Multiple criteria decision making
Indicators source	Literature review, questionnaires	Case study	Postal and telephone surveys	N/A	Multi-criteria Decision Aiding Hybrid Algorithm (THOR)
Indicators	Energy costs	Benefit	Transportation costs	Transfer costs	Investments
	Labour costs	Purchasing cost savings by reusing and recycling	Landfill charge	Taxes	Operational costs
	Transportation costs	Revenue from selling of scrap waste materials	Recycling charge		Disposal/treatment costs
	Retail price	Waste transportation cost saving	Extra recycling charges		
		Cost savings from landfill charge	Primary aggregates prices		
		Cost	Recycled aggregate costs (detailed)		
		Collection and separation costs	Extra recycling costs		
		Equipment purchasing cost	Imposition of taxes -- landfill		
		Storage costs	Subsidy -- recycling		
		Transportation costs			
Authors	Shen et al., (2009)	Tam et al., (2010)	Zhao et al., (2010)	Yuan et al., (2011)	Zhao et al., (2011)
Method	Original model	Original model	Original model	Original model	SD/Original model
Indicators source	Case study	Questionnaire survey and structured interviews	Case study	Secondary data	Secondary data
Indicators	Landfill charges	Reducing project cost by using recycled materials	Capital costs	Capital value	Profit
	Transportation costs	Saving transportation costs	Construction works	Energy yield ratio	Unit recycling cost

	Placing costs		Cost for equipment		Extra revenue from location advantage
			Land costs		
			Opportunity costs		
			Operational costs		
			Labour costs		
			Energy costs		
			Disposal costs		
Authors	Manowong, (2012)	Srour et al., (2013)	Yuan (2013)	Tam et al., (2014)	Ding et al., (2016)
Method	Structural equation modelling	Original model	Original model	SD/Original model	SD
indicators source	Questionnaire	Case study	Literature review	Secondary data	Secondary data and interview
Indicators	Economic sustainability	Economic indicators	Economic performance	Increasing GDP	Cost of waste collection
	Economic incentive	Daily labour rates	Cost of waste collection, sorting and separation	Illegal dumping costs	Onsite sorting costs
	Cost effectiveness	Site clearing, levelling and filling costs	Cost of waste reuse	Transportation costs	Illegal dumping disposal costs
	Expenditure	Border fence costs	Waste recycling costs	Landfill charge	
	Revenue	Pre-fabricated site offices costs	Waste transportation costs	Saving costs	
	Recycling interests	Annual increase of operating costs	Disposing waste in landfill costs	Recycling costs	
		Maintenance and insurance costs	Penalty paid due to illegal dumping of waste	Landfill costs	
			Revenue from selling waste materials		
			Saving in waste transportation		
			Saving in cost for disposing of waste in landfill		

3.5.3 Social impacts assessment indicators

Compared to environmental and economic impact assessment, social impacts assessment has attracted less attention. Typically, social impacts assessment closely relates to different stakeholder groups throughout the life cycle of construction and demolition activities, including employees, consumers and local communities. Social impact assessment often concerns issues like wages, health and safety, and access to education. The barriers to conducting adequate social impact assessment lie in that the issues at stake are wide-ranging and often difficult to quantify in a meaningful way (Goedkoop et al., 2008).

The selection of social impacts assessment indicators shows significant differences among studies between stakeholder-based and impact category-based. For instance, Klang et al. (2003) focused on the worker's point of view, while some studies consider the public apart from employees (Yuan, 2012, 2013). From the impact category-based structure, Manowong (2012) selected wide-ranging indicators such as employees' health, exposure to risks, safety, gender equality, workplace diversity, fairness and so on; on the other hand, Chung and Lo (2003) selected an abstract indicator, namely social acceptability and equity to assess the social performance of C&D waste management. Table 3.7 summarises the methods and indicators for assessing the social impacts of C&D waste.

Since there are wide-ranging aspects in considering social issues, it is suggested that the first step is the identification of most relevant aspects. Apart from the methods and indicators in previous studies, there are also some references available for conducting a social impacts assessment (Goedkoop et al., 2008), such as the UNEP SETAC (Benoît-Norris et al., 2011), the Global Reporting Initiative (GRI), the United Nations Global Compact (UNGC), and the ISO 26000 for social responsibility.

Table 3.7: Indicators for social impacts assessment

Authors	Chung & Lo, (2003)	Klang et al., (2003)	Manowong (2012)		Yuan (2012)	Yuan (2013)
Method	Original model	Original model	Structural equation modelling		SD	Original model
Indicators source	Review	Literature, questionnaires, documents	N/A	Waste handling	Case study/literature review	Literature review
Indicators	Social acceptability and equity	Worker's evaluation of physical working environment	Health impact	Safety training	Illegal construction waste dumping on society image	Practitioners' awareness to manage waste
		Worker's estimates of socio-psychological work environment	Accident prevention	Gender equality	Physical working environment	Provision of job opportunities
		Percentage of workers that after the project would consider working within the field	Casualty prevention	Gender equality	Job opportunities	Physical working condition
		Degree of employment after finishing the project	Health condition	Gender respect	Operative safety	Impacts on long-term health
			Exposure to risks	Workplace diversity	Practitioners long-term health	Safety of operatives in conducting waste management
			Mental health	Fairness		Public satisfaction about C&D waste management
			Health policy & practice	Stakeholder participation		Public appeal for regulating illegal waste dumping
			Health awareness	Susceptibility		Impacts of illegal waste dumping on social image

3.6 Approaches for impacts assessment of C&D waste management

3.6.1 Overview of impacts assessment of C&D waste management

Although significant achievements have been made to assess C&D waste management performance in recent years, lack of a general framework to cover critical aspects in assessing C&D waste management performance is evident. With such a framework, researchers can quickly understand prior development of performance assessment methods and indicators in the field; practitioners and policymakers can gain a comprehensive understanding of the significance and complexity of environmental, economic and social impacts of C&D waste, which is helpful to improve practice. Based on in-depth analysis of the selected sample, this study proposes a framework for C&D waste management performance assessment research in terms of system boundary, research scale and performance aspects (see Figure 3.2).

C&D waste management performance assessment		Sustainability based thinking	Systems thinking	Life cycle thinking
System boundary	Particular activities	(Chung and lo, 2003; Shen et al., 2009; Zhao et al., 2010; Yuan et al., 2011; Dahlbo et al., 2015; Gomes et al., 2008; Klang et al., 2003; Begum et a., 2006; Duran et al., 2006; da Rocha et al., 2009; Merino et al., 2010; Tam et al., 2010; Saez et al., 2013)	(Zhao et al., 2011; Ye et al., 2012; Yuan, 2012; Tam et al., 2014; Ding et al., 2016)	
	Entire life cycle			(Bohne et al., 2008; Mercante,et al.,2012; Simion et al.,.2013; Stefania et al., 2015; Kucukvar et al.,2016; Penteado et al..2016; Zambrana et al.,.2016; Ortiz et al., .2010; Chau et al., 2017)
Research scale	Project level	(Lu et al., 2009)		(Ortiz et al., 2010; Chau et al., 2017; Wang et al., 2018)
	City level	(Chung et al.. 2003; Shen et al.,.2009; Zhao et al. 2010; Yuan et al..2011)	(Zhao et al.,.2011; Ye et al.,.2012; Yuan et al.,.2012; Tam et al.,2014; Ding et al.,.2016)	(Bohne et al., 2008; Wu et al., 2015)
	National level	(Dahlbo et al.,.2015; Gomes,et al.,.2008; Klang et al.,. 2003; Begum et al.,.2006; Duran, et al.,.2006; da Rocha, et al.. 2009; Merino, et al.,.2010; Tam et al., 2010; Saez, et al., 2013)	(Marzouk et al.,.2014)	(Mercante et al., 2012; Penteado & Rosado, 2016)
Performance aspects	Environmental	(Dahlbo et al.,.2015; Gomes et al., 2008;Chung et al.,. 2003; Klang et al., 2003; Roussat et al.,.2009; Merino et al.,2010; Tam et al., 2010; Yuan et al.,2011; Yuan .2013)	(Ye et al.,.2012; Marzouk et al.,.2014; Tam et al.,.2014; Manowong et al.,.2012; Marrero et al.,2017)	(Bohne et al., 2008; Mercante et al.,2012; Simion et al.,.2013; Stefania et al.,2015; Kucukvar et al., 2016; Penteado et al., 2016; Zambrana et al.,2016; Ortiz,et al., 2010; Chau,et al., 2017)
	Economic	(Lu et al.,.2009; Dahlbo et al.,.2015; Gomes, et al., 2008; Chung et al.,. 2003; Klang et al., 2003; Begum et al.,2006; Duran, et al.,.2006; da Rocha et al., 2009; Shen et al.,.2009; Zhao et al., 2010; Srour et al.,.2014; Yuan, 2013)	(Zhao et al., 2011; Marzouk, et al., 2014; Tam et al., 2014; Manowong et al.,.2012; Ding, et al., 2016)	(Bohne et al., 2008; Kucukvar et al.,.2016)
	Social	(Chung et al., 2003; Klang et al., 2003; Yuan, .2013)	(Yuan, .2012; Manowong et al.,2012)	

Figure 3.2: Overview of impacts assessment of C&D waste management

In terms of the research objectives, previous life cycle thinking based studies focus more on the entire life cycle of C&D waste, from waste generation to its final disposal (Bohne et al., 2008; Chau et al., 2017; Kucukvar et al., 2016; Mercante et al., 2012; Ortiz et al., 2010; Penteado & Rosado, 2016; Simion et al., 2013; Wang et al., 2018; Wu et al., 2015). System thinking based studies focus mainly on the development of C&D waste systems containing a series of waste management activities such as reuse, recycling and landfilling (Ding, et al., 2016a; Marzouk & Azab, 2014; Tam et al., 2014; Ye et al., 2012; Yuan, 2012; Zhao et al., 2011). Sustainability based studies prioritise the assessment of particular C&D waste management activities such as recycling and landfilling (Butera et al., 2015; Dejkovski, 2016; Ding et al., 2016; Kucukvar et al., 2016; Marrero et al., 2017; Roussat et al., 2009; Stenis, 2005; Srour et al., 2013; Wang et al., 2004; Yuan, 2012).

Considering the research scale, studies from different research strands show very different priorities. The majority of system thinking based studies focus primarily on C&D waste management issues at a city level (Ding et al., 2016; Tam et al., 2014; Ye et al., 2012; Yuan, 2012; Zhao et al., 2011) while sustainability based studies favour issues at a national level more than at city or project levels (Begum et al., 2006; Duran et al., 2006; Tam, 2008). The distribution of life cycle thinking based studies is somehow equally distributed among different levels.

It can be observed that not many studies have been conducted on assessing the social performance of C&D waste management (Manowong, 2012; Yuan, 2012). The life cycle thinking studies mostly concentrate on environmental issues of C&D waste management (Butera et al., 2015; Kucukvar et al., 2016). Given the priority of the current LCA method, there is no attempt to consider social issues into life cycle thinking studies when assessing C&D waste management performance. The distribution of studies on performance aspects is identical between sustainability based and systems thinking based research. They pay much more attention to environmental and economic aspects of C&D waste management.

3.6.2 General procedure for impacts assessment of C&D waste management

An analysis of the methodologies adopted in selected C&D waste management performance assessment studies tease out some common research procedures. By integrating and streamlining critical research processes extracted from previous studies of the three themes (i.e. sustainability based thinking, life cycle thinking, and systems thinking), it is proposed that a five-step procedure for assessing impacts of C&D waste management (Figure 3.3).

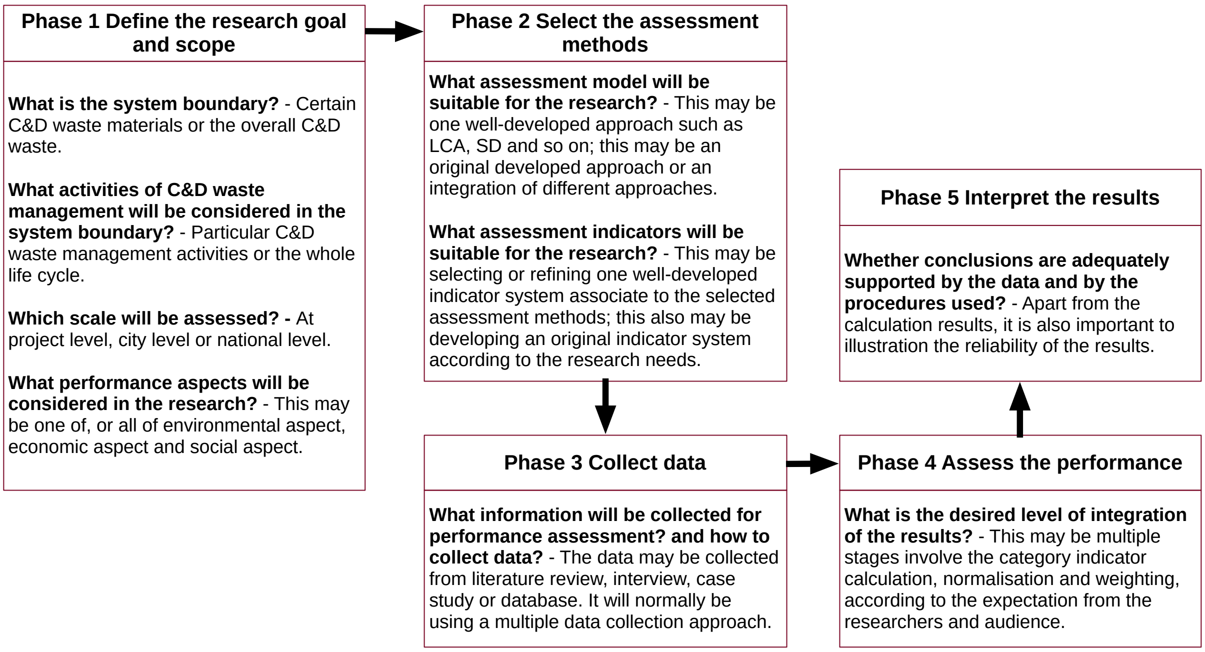


Figure 3.3: General procedures for impacts assessment of C&D waste management

Generally, the first step is to define the research goal and scope, which is critical in determining the selection of methods and designing the research. At this stage, four questions should be considered:

- What is the system boundary? Considering certain types of C&D waste materials or the overall C&D waste.
- What activities (scenarios) of C&D waste management will be considered? Concentrating on particular C&D waste management activities or assessing the whole life cycle.
- Which scale will be assessed? Scoping the study at project level, city level or national level.
- And what performance aspects will be involved? Either focusing on one of the three dimensions of performance (i.e. environmental, economic and social), or covering all of them. Previously goals and scopes are defined by various elements, which may be an overall C&D waste management system at project, city or national level (Bohne et al., 2008), or maybe the treatment of one or several C&D waste materials (Butera et al., 2015).

The second step is to select assessment methods, considering two main aspects:

- What assessment model will be suitable? This may be resolved by selecting a well-developed approach such as LCA and SD (Bohne et al., 2008; Chau et al., 2017; Ding, et al., 2016a; Kucukvar et al., 2016; Marzouk & Azab, 2014; Mercante et al., 2012; Ortiz et al., 2010; Penteado & Rosado, 2016; Simion et al., 2013; Wang et al., 2018; Wu et al., 2015; Yuan, 2012), or considering an originally developed approach or integration of different approaches (Ajayi et al., 2015).

- The second question is what assessment indicators will be suitable. The study may select or refine a well-developed indicator system associated with selected assessment methods (Ortiz et al., 2010), or develop an original indicator system according to research needs (Marrero et al., 2017). The selection of criteria is frequently achieved through a literature survey.

The third step is to collect data, taking into consideration: what information will be collected for assessment and how data should be collected. The data may be collected from the literature review, interview and case study, or via databases. Generally, multiple data resources would be adopted in such studies (Dahlbo et al., 2015; Penteado & Rosado, 2016).

The fourth step is to assess the impacts. It is worth considering here what the desired level of integration of results is, and this in turn will affect accuracy and presentation of results. There are multiple stages involving category indicator calculation, normalisation and weighting, according to the expectations of researchers and audience (ISO 14040/44). Most studies provide quantitative results while sometimes qualitative recommendations for policy development are included (Saez et al., 2013; Yuan, 2013).

The fifth and final step is to interpret the results. Typically, this is associated with scenario analysis of results, which is critical for findings' implications. It is also important to consider whether conclusions are adequately supported by the data and procedures used. Besides the calculation results, it is crucial to indicate reliability of results. For instance, when adopting an LCA method, the result interpretation includes uncertainty analysis, sensitivity analysis, analysis and inventory analysis (ISO 14040/44).

3.7 Summary

This chapter provided a review of approaches for assessing the impacts of C&D waste management activities. By analysing the studies in terms of research methods, data collection methods and critical indicators employed, the study assessed the adoptability of developed methods regarding theoretical development and limitations.

It was found that significant efforts have been made for developing models to assess the impacts of C&D waste management. Three main assessment approaches, namely sustainability based methods, system thinking methods, and life cycle thinking methods have been developed in prior studies. A considerable percentage of previous studies used well-developed methods, such as LCA and SD, for assessing impacts of C&D waste management activities. Research priorities vary according to research strands. For instance, the majority of studies adopted LCA, mainly concentrating on the environmental aspect due to the nature of the method. SD more broadly covered various aspects including economic, environmental and social aspects. Although there are a number of studies employing SD to assess C&D waste management performance, the validation of the SD model was controversial in many discussions due to the nature of its methodology.

It was evident that compared to environmental and economic aspects, the social aspect attracted less attention, though the social aspect is critical for understanding overall impacts of C&D waste management. Significant studies indicated that the economic feasibility of C&D waste management strategies depended on various factors, such as economies of scale, methods of recycling, cost of landfill, transportation distance, and so on.

In terms of data collection, different research strands adopted different methods. For instance, sustainability based studies mainly use interview, questionnaires or case study to validate the adoptability of models; data collection of system dynamics (SD) studies are based on multiple methods, including theoretical assumption, experts' estimation and secondary data; LCA studies in relation to the foreground data used to create the modelling system, normally collected data from specific companies via interview or questionnaires. The most welcome sources for background data in C&D waste LCA studies is the *Ecoinvent* database.

By integrating and streamlining critical research processes extracted from previous studies, this chapter has provided a useful and generic procedure for assessing C&D waste management performance. With the consideration of research objectives, LCA is selected as the main method to quantify the impacts of cross-regional mobility of C&D waste in Australia in this study. The knowledge on current performance assessment practices in C&D waste management and the proposed framework supply the basis for the development of sound C&D waste management methods and make it possible to better understand environmental, economic and social impacts for C&D waste management.

Chapter 4. Methodology and methods

4.1 Introduction

This chapter provides an overview of the research design used and methods. As discussed in Chapter 1, the study is designed to investigate cross-regional mobility of C&D waste and related impacts. Three main research objectives are: (1) the investigation of the management and cross-regional mobility of C&D waste in Australia; (2) the evaluation of impacts of C&D waste cross-regional mobility in Australia; and (3) the development of optimisation strategies for managing C&D waste cross-regional mobility in Australia.

To address the objectives, a research framework is developed in section 4.2. Section 4.3 investigates management and cross-regional mobility in Australia, including treatment and management of C&D waste in Australia, particularly cross-regional mobility of C&D waste in Australia (**The contents have been published in associated publications 1 and 3 listed on page xiii**). Section 4.4 discusses the development of impacts assessment models for C&D waste cross-regional mobility, including environmental, economic and social impacts. The approach to developing optimisation strategies for C&D waste cross-regional mobility in Australia is discussed in section 4.5.

Methodological approaches were developed based on multiple disciplines, such as construction management, environmental science and industrial ecology. Methods and results will be framed within the language of construction management research.

The ethics application for this research has been reviewed by the Low Risk Human Research Ethics Review Group and meets the requirements of the National Statement on Ethical Conduct in Human Research (2007) involving low risk for research participants (Approval number: H-2018-244). See Appendix A for approval letter.

4.2 Research framework

This study aims to understand cross-regional mobility of C&D waste issues and related impacts in Australia. Furthermore, recommendations will be made that enable Australian C&D waste management departments to determine whether to encourage cross-regional mobility of waste, and if so, at what level.

According to the research questions three main objectives will be addressed: (RO1) investigating management and cross-regional mobility of C&D waste in Australia; (RO2) evaluating impacts of cross-regional mobility of C&D waste in Australia; (RO3) Making recommendations in terms of management of cross-regional mobility of C&D waste. Figure 4.1 illustrates the research framework.

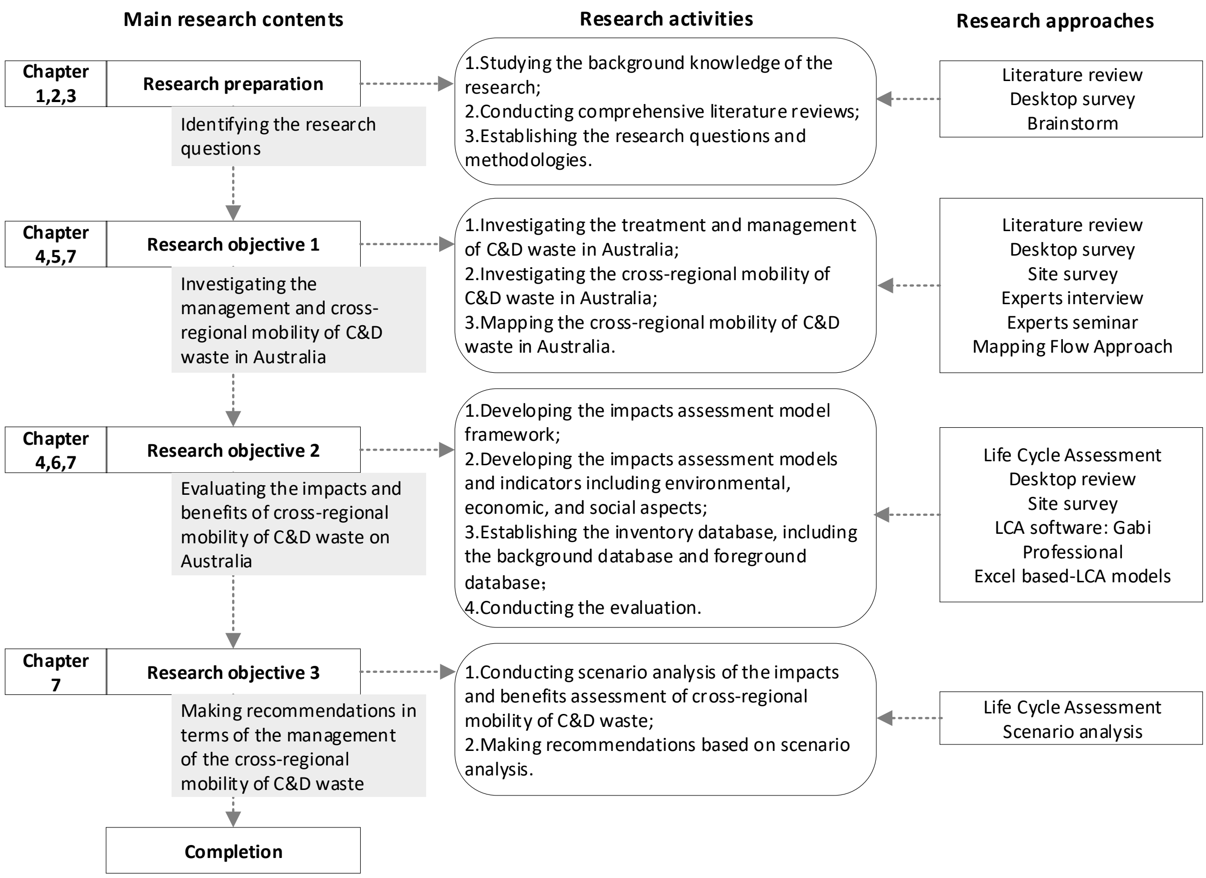


Figure 4.1: Research framework

RO1: To investigate cross-regional mobility of C&D waste in Australia, the study mainly focuses on two aspects: investigating the treatment and management of C&D waste in Australia and cross-regional mobility of C&D waste in Australia. The methodologies are illustrated in section 4.3. The main results will include compositions and generation of C&D waste in Australia (see section 5.1 in Chapter 5), fates and flows of C&D waste in Australia (see section 5.2 in Chapter 5), and C&D waste cross-regional mobility in Australia (see section 5.3 in Chapter 5).

RO2: To assess impacts of cross-regional mobility of C&D waste in Australia, a series of methods based on Life Cycle thinking theory considering economic-social-environmental aspects were developed in the study (section 4.4). Firstly, the assessment model framework is developed based on a systematic methodological literature review (Chapter 3) and it is illustrated in section 4.4.1; secondly, indicators for assessment models are selected (sections 4.4.2 to 4.4.4); thirdly, a series of quantification equations are developed (section 4.4.5); the inventory database including foreground database and background database to operate the model is collected from various sources (section 4.4.5); and scenario settings to analyse impacts and benefits of cross-regional mobility of C&D waste in different situations are discussed in section 4.4.6. The results will be presented in Chapter 6.

RO3: To develop optimisation strategies for the management of cross-regional mobility of C&D waste in Australia, a Scenario Analysis Method will be employed in this study (section 4.5). The Australian C&D waste cross-regional mobility network developed in this study will discuss a series of potential scenarios for treating C&D waste; the well-established impacts assessment model will then provide methods to assess performance for each scenario in the network. These recommended strategies will be discussed in Chapter 7.

4.3 Investigating management and cross-regional mobility

One of the research goals is to understand C&D waste treatment and management, particularly cross-regional mobility of waste in Australia. It concentrates on C&D waste generated in Australia, covering all eight Australian states and territories, including the Australian Capital Territory (ACT), New South Wales (NSW), Northern Territory (NT), Queensland (QLD), South Australia (SA), Tasmania (TAS), Victoria (VIC), and Western Australia (WA). To achieve the aims of this study, a specific research framework for investigating management and cross-regional mobility of C&D waste in Australia is developed, as shown in Figure 4.2.

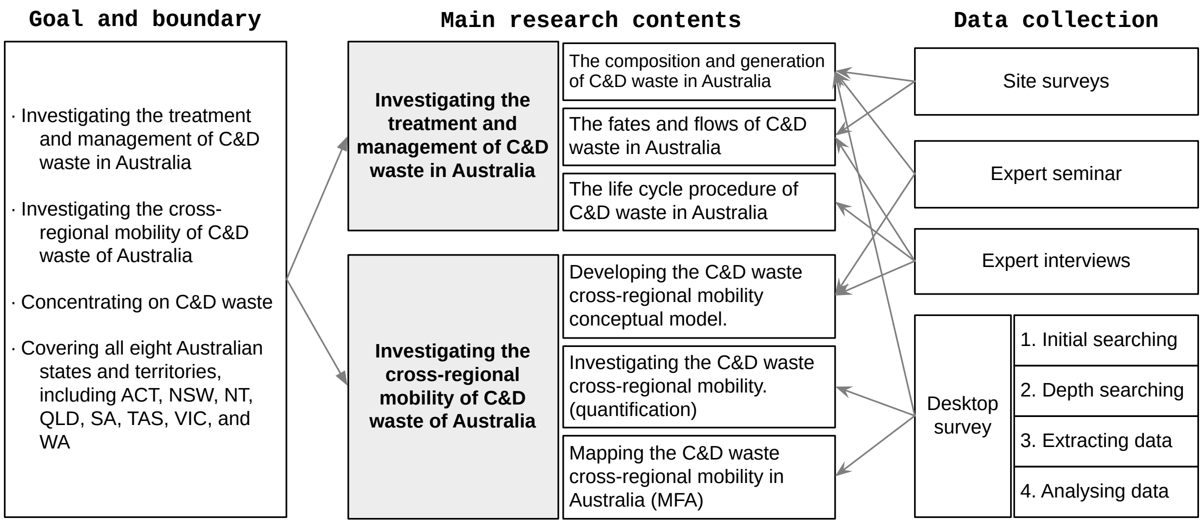


Figure 4.2: Research framework for investigating management and cross-regional mobility

4.3.1 Investigating the treatment and management of C&D waste in Australia

To investigate the treatment and management of C&D waste, particularly compositions, generation, fates, flows and the life cycle procedure of C&D waste in Australia, a mixed methods approach including site survey, expert seminar, expert interview and desktop survey were conducted to collect the data. The data collection details are discussed in section 4.3.3.

Generally speaking, the desktop survey was conducted to obtain the list of main compositions of C&D waste generated in Australia and the site survey was conducted to obtain the images of the main C&D waste materials samples in the construction sites. Expert seminar gained in-depth understanding of C&D waste management in Australia. The desktop survey also mapped generation trend and distribution of C&D waste in Australia in recent years. The results are shown in section 5.1 in Chapter 5. The site survey was used to identify flows and life cycle of C&D waste in Australia and also provided pictures for mapping the flows of C&D waste. The while desktop survey was employed to quantify percentages of C&D waste flow to different destinations such as C&D waste recycling operations, organic waste processing operations, C&D waste landfill and illegal dumping. The results are shown in section 5.2 in Chapter 5.

4.3.2 Investigating cross-regional mobility of C&D waste in Australia

4.3.2.1 Developing the C&D waste cross-regional mobility conceptual model

Cross-regional mobility of C&D waste means moving waste cross-border, that is, some C&D waste is transported cross-border to be processed or disposed of in other regions. This will have a significant impact on the environment, the economy and society in relation to a sustainable Australia. C&D waste cross-regional mobility is a concept that can be compared to intra-regional mobility of C&D waste. C&D waste is heavy and has a low unit economic value thereby making the transport of C&D waste inefficient. Previous studies assume C&D waste is processed at the local level in the community rather than transported to other regions.

Based on interviews with C&D waste experts in Australia (see section 4.3.3), a conceptual model has been developed to present the C&D waste cross-regional mobility phenomenon, as shown in Figure 4.3. Apart from a percentage of C&D waste being processed intra-regionally, a considerable percentage of C&D waste has been transported cross-border and treated in other regions. Based on this conceptual model, the study collects C&D waste generation, treatment and cross-regional mobility data and creates maps of C&D waste cross-regional mobility in Australia.

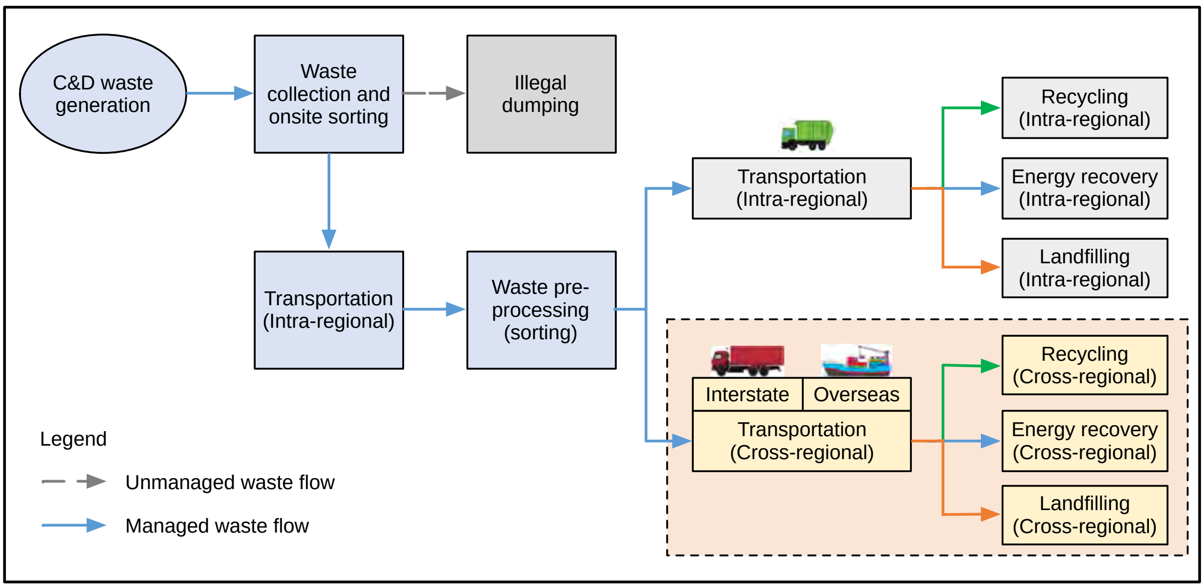


Figure 4.3: C&D waste cross-regional mobility conceptual model

4.3.2.2 Quantifying C&D waste cross-regional mobility in Australia

Quantifying the amount of waste is essential in conducting material flow analysis (Bringezu & Moriguchi 2002). To quantify C&D waste cross-regional mobility in Australia, categories of C&D waste related to cross-regional mobility network must be identified and the amount of each category of waste must be quantified. Specifically, categories of C&D waste are transported across regions and treated in regions differently from the original generation region, and accordingly the volume of waste must be quantified. According to the *National Waste Report 2018* (Dee, 2018), the core composition of C&D waste materials consist of eight categories: C1-Masonry materials (including asphalt, bricks, concrete, and plasterboard and cement sheeting), C2-Metals (including steel, aluminium and non-ferrous metals), C3-Organics (including garden organics and timber), C4-Paper and cardboard, C5-Plastics, C6-Glass, C7-Textiles, leather and rubber and C8-other.

Based on the cross-regional mobility conceptual model and core composition of C&D waste, a quantification model is developed via Excel to quantify C&D waste cross-regional mobility in Australia (see Figure 4.4).

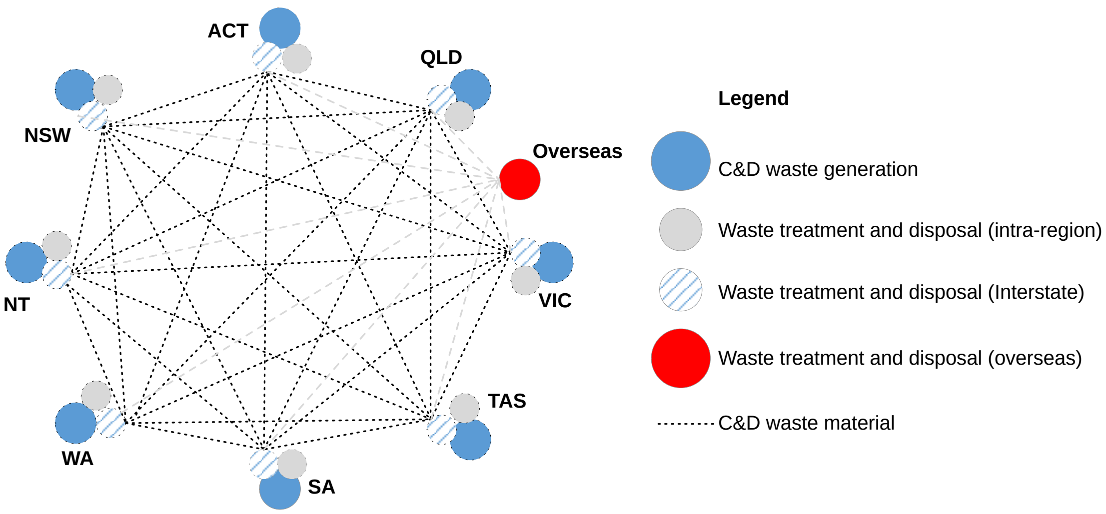


Figure 4.4: C&D waste cross-regional mobility quantification model

4.3.2.3 Mapping cross-regional mobility of C&D waste in Australia

To map cross-regional mobility, Material Flow Analysis (MFA) is proposed for this study. MFA is an analytical method to quantify flows and stocks of materials or substances in a well-defined system (Bringezu and Moriguchi, 2002). This method has been employed to quantify the generation of C&D waste in certain areas in previous studies (Shen et al., 2004; Wu et al., 2017). MFA in previous studies was mainly conducted in a local-closed boundary, determined by research aims. As the research goal in this study is looking at the cross-regional mobility of C&D waste, the traditional MFA method has to be improved accordingly to match the research question 2 in this study. One MFA improvement in this study is to consider geographic mobility of C&D waste, particularly designed to track mobility routes of waste. Specifically, geographic mobility will be considered in the improved MFA method, when mapping mobility routes. The results are shown in section 5.3 in Chapter 5.

4.3.3 Data collection and data sources

Data collection methods in this study include: 1) collecting qualitative data via site surveys, expert seminars and expert interviews; 2) collecting quantitative data via desktop survey.

4.3.2.1 Site surveys, expert seminars, and expert interviews

To investigate the composition and flow of C&D waste in Australia, a series of site surveys, expert seminars and expert interviews were conducted from November 2018 to July 2019. To cover more construction and demolition project types, this study selected a wide range of projects for site surveys. Due to visit permissions, the study was able to conduct 8 site surveys on construction and demolition projects. Multiple site surveys can provide sufficient information about C&D waste generation on site. These site surveys include three high-rise apartment projects, an aged care project, two school redevelopment projects, a hospital reconstruction project and railway station reconstruction project.

To gain in-depth understanding of C&D waste management in Australia, expert seminar was hosted on May 30, 2019 with 10 C&D waste management related experts invited, including three C&D waste recyclers, two building components suppliers, three constructors/builders, one C&D waste management related government officer and an academic. Selection of experts was mainly based on their expertise and availability.

To collect specific data on C&D waste treatment such as recycling, landfilling, and cross-regional mobility, special site surveys for two C&D waste recycling centres and two expert interviews with senior managers of renowned C&D waste recyclers in South Australia were conducted in July 2019. Tables 4.1 and 4.2 detail information on site surveys, expert seminar and expert interviews.

Table 4.1 Information on site surveys

Activity	Organisation/construction type	Number	Date
Site surveys	Construction/demolition site – high-rise apartments	3	Nov, Dec 2018
	Construction/demolition site – aged care project	1	April 2019
	Construction/demolition site – school project	2	April 2019
	Construction/demolition site – hospital	1	June 2019
	Construction/demolition site – railway station	1	May 2019
	C&D waste recycling centre	2	July 2019

Table 4.2 Information on expert seminars and expert interviews

Activity	Organisation/expert type	Working experience (years)	Date
Expert seminar	C&D waste recycler 1	20	May 2019
	C&D waste recycler 2	13	
	C&D waste recycler 3	8	
	Building components supplier 1	11	
	Building components supplier 2	6	
	Constructor/builder 1	15	
	Constructor/builder 2	12	
	Constructor/builder 3	8	
	Government officer (C&D waste management related)	20	
	Academic	30	
Expert interview	Senior manager of renowned C&D waste recycler 1	20	July 2019
	Senior manager of renowned C&D waste recycler 2	13	

4.3.2.2 Desktop survey

A desktop survey was conducted to investigate generation and cross-regional mobility of C&D waste in Australia. Firstly, an initial search was conducted in November 2018 via Google to identify main data sources; secondly, an in-depth search on Australian governmental websites and industrial association websites was conducted to download report related to C&D waste information; and thirdly, the data was exacted and analysed from December 2018 to March 2019. The data exaction and analysis took time because the data structure in some data sources was complex. Some data are combined with that of municipal solid waste (MSW), commercial and industrial (C&I) waste, and construction and demolition (C&D) waste, which need to be identified and separated carefully.

Multiple data sources, including relative C&D waste open-access documents (e.g. the *National Waste Report 2018),* report at state level (e.g. *South Australia's Waste and Resource Recovery*

Infrastructure Plan) and databases have been surveyed. The data sources are listed in Table 4.3.

Table 4.3 Desktop survey list

Region	Report name	Organisations
National	*National Waste Report 2018*	*Department of the Environment and Energy*
ACT	*Waste Feasibility Study -- Roadmap and Recommendations 2018*	*ACT Government*
VIC	*State-wide Waste and Resource Recovery Infrastructure Plan (Victoria 2017)*	*Sustainability Victoria*
	Victorian Recycling industry Annual Report 2015--2016	*Sustainability Victoria*
	Victorian Recycling industry Annual Report 2016--2017	*Sustainability Victoria*
NSW	*Waste and Resource Recovery Infrastructure Needs Report 2017--21*	*NSW EPA*
	Waste Avoidance and Resource Recovery Strategy Progress Report 2017--18	*NSW EPA*
	Calculation method for waste generation, recycling and diversion	*NSW EPA*
QLD	*Recycling and Waste in Queensland 2018 Report*	*Queensland Government*
	Transforming Queensland's Recycling and Waste Industry Directions Paper	*Queensland Government*
SA	*South Australia's Recycling Activity Survey 2017--18 Report*	*Green Industries SA*
WA	*Recycling activity in Western Australia 2016--2017*	*Waste Authority WA*
NT	*National Waste Report 2018*	*Department of the Environment and Energy*
TAS	*National Waste Report 2018*	*Department of the Environment and Energy*

4.3.4 Limitations

Despite a comprehensive research plan being developed, there are some limitations to the research. For instance, the data on fates and flows of C&D waste are mainly based on expert seminars and expert interviews. This data relies on the experience of experts. Although the expert subjects selected for the study are renowned industry experts, their knowledge may not cover all aspects of C&D waste management. Due to time limitations with interviews and seminars, experts may not be able to provide all the information they have.

Apart from this, as the quantification data is mainly based on various open-access reports and databases, the data quality may differ from case to case. This is usually due to the difficulty of the data providers collecting accurate data. The most significant issue is that waste streams are not fully separated in some reports, as recycling operators cannot always report the source of all materials. Consequently, some assumptions and reallocations have been made in the study—when accurate data is not available, cross-regional mobility quantification data on a certain type of waste material was calculated by multiplying the percentage of C&D waste material accounting for total weight of type of waste by total weight of same waste material transported interstate/overseas.

4.4 Developing the impacts assessment model for C&D waste cross-regional mobility

This section will discuss the development of impacts assessment model for cross-regional mobility of C&D waste in Australia. As discussed in Chapter 1, this study expands C&D waste research theory from a local-closed issue to a cross-regional mobility issue. A concept for C&D waste cross-regional mobility impacts is developed below in Figure 4.5. Previously, C&D waste was processed, recycled and disposed of in the same region where waste was generated (Figure 4.5a). Due to the C&D waste cross-regional mobility, the amount of waste being processed, transported, recycled, energy recovered and landfilled in the waste generation region and the waste import regions has been affected (Figure 4.5b). All activities involving C&D waste processing and recycling need inputs of environmental, economic and social resources, to generate certain outputs. Hence cross-regional mobility of C&D waste will affect environmental, economic and social performance of C&D waste processing and recycling systems in regions involved in waste mobility activities (Figure 4.5c).

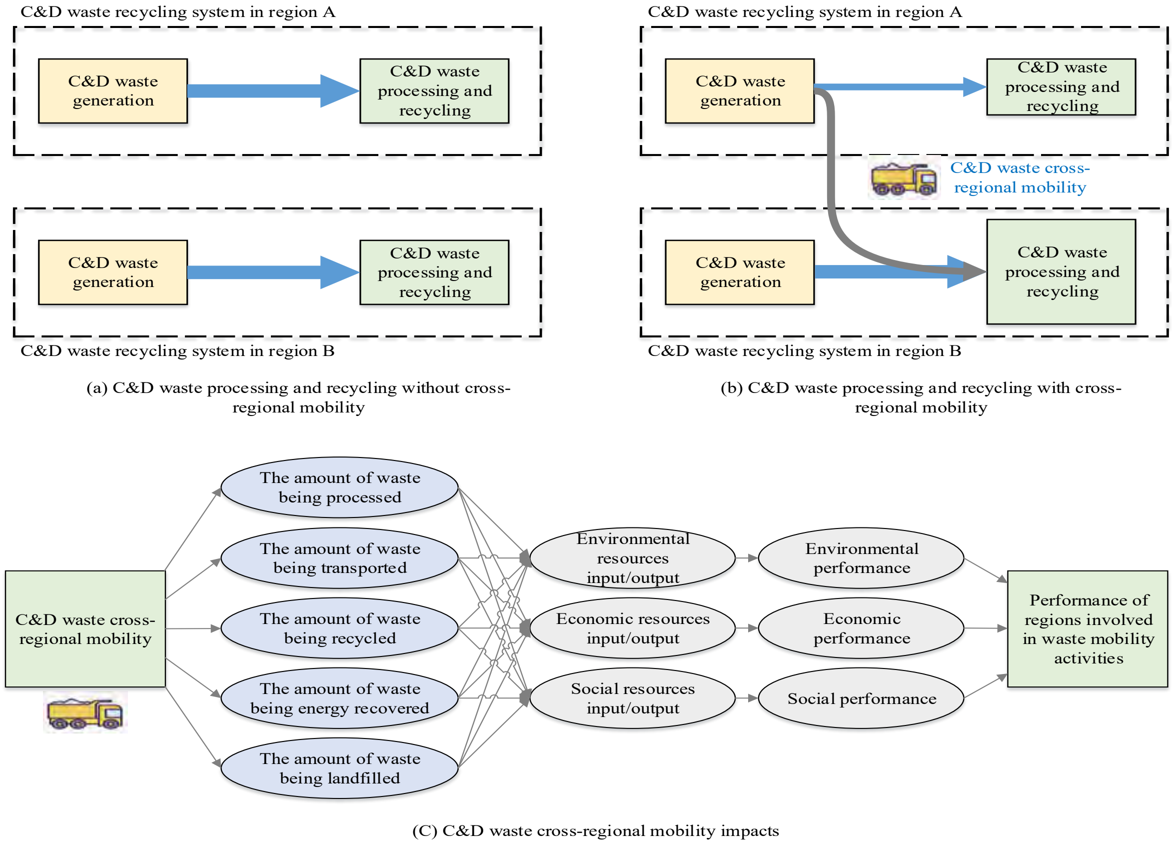


Figure 4.5: C&D waste cross-regional mobility impacts concept

4.4.1 Developing the impacts assessment model framework

As activities in each stage in the life cycle of C&D waste (namely, from waste generation to final disposal) affect the performance of the whole system, it is necessary to exam the system from a life cycle perspective. Hence, a model to assess the impacts of C&D waste cross-regional mobility based on life cycle thinking theory is developed in this study.

Regarding life cycle thinking, life cycle assessment (LCA) is a widely employed approach to assess impacts (i.e. environmental impacts) of a certain product or procedure during its life cycle (ISO, 2006). LCA considers the impacts of a product system 'from the cradle to the grave' (McDougall et al., 2008). For the LCA, the International Standards Organisation (ISO) have published the *ISO 14040* and *ISO 14041* to introduce the principles and framework, requirements and guidelines for the assessment of environmental impacts. According to *ISO 14040*, the phases of LCA consist of four stages, namely, goal & scope definition, inventory analysis, impact assessment and interpretation (ISO 14040). However, ISO standards are defined in general language, which makes it difficult to assess whether LCA has been made, step by step, according to the standard. Hence, a specific model is required when conducting a LCA study.

Although significant efforts have been made to develop methods to assess the economic and social impacts from a variety of disciplines, there is no worldwide standard for economic impacts. Hence, assessment models should be designed to suit each situation accordingly. Considering environmental, economic and social impacts, a framework to assess the impacts of cross-regional mobility of C&D waste is developed in this study (see Figure 4.6).

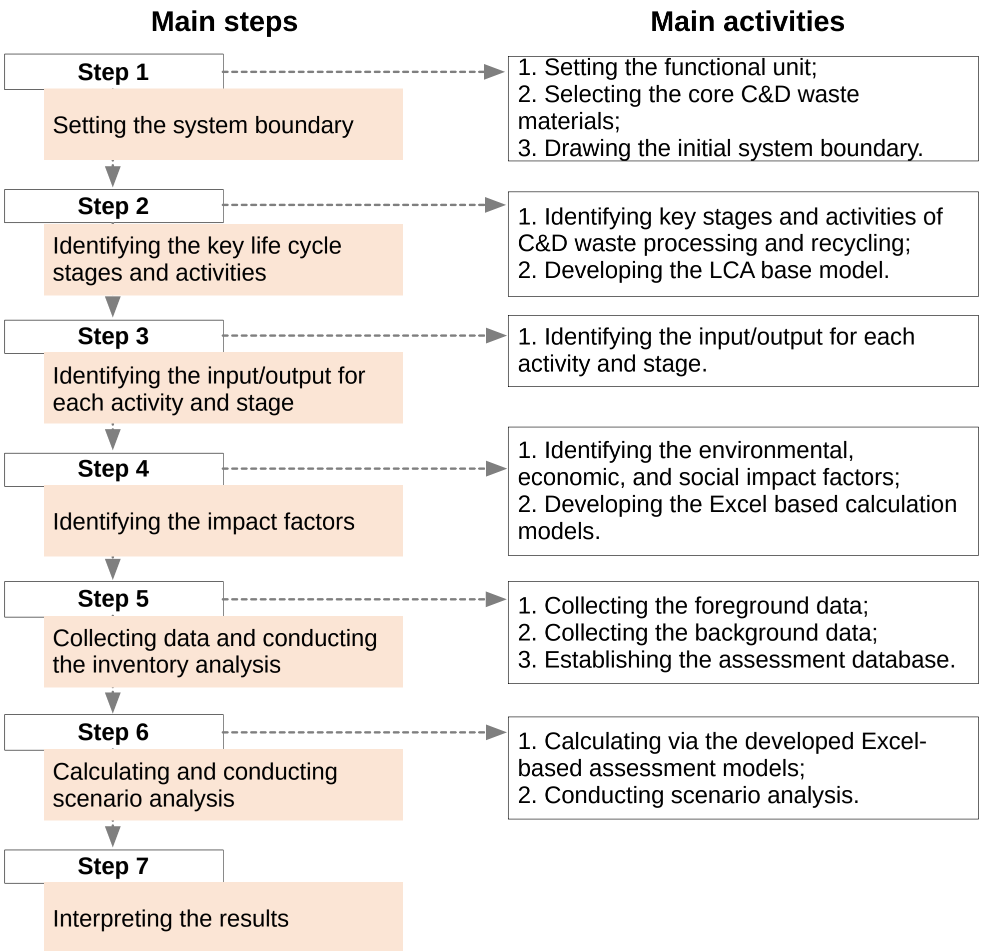


Figure 4.6: Impacts assessment model framework

4.4.1.1 Setting the system boundary

For any LCA-based study, the first step is to define the goal and scope, namely to set the system boundary. The requirements include the functional unit, initial system boundaries, and criteria for inclusion of inputs and outputs, and dealing with the multifunctional process. The most critical methodological choices, assumptions and limitations should be clearly described in the first phase (Goedkoop et al., 2008).

- Setting the functional unit

According to the literature review, it is found that almost all previous LCA-C&D waste studies adopted 1 ton (1 ton = 1,000 kg) of C&D waste consisting of various waste fractions as the functional unit. To keep the results constant and to make results convenient to be referred to in future research, the study follows the tradition of setting the functional unit (1t) as described above.

- Selecting core C&D waste materials

Although C&D waste consists of a number of materials which vary among projects, it is necessary to identify core C&D waste materials for consideration. Based on the results in section 4.3, *cross-regional mobility* core C&D waste materials have been identified. They are: masonry materials (e.g. asphalt, bricks, concrete, rubble, plasterboard and cement sheeting), metals (e.g. steel, aluminium and other non-ferrous materials), organics (e.g. garden organics and timber), paper and cardboard, plastics, glass, textiles and other unclassified materials (Table 4.4).

Table 4.4: Core waste materials percentage used in the calculation

Waste category	Percentage
Masonry	83.4%
Metals (steel 80%, aluminium 5%, copper 15%)	6.5%
Organics (timber)	4.9%
Paper & cardboard	0.5%
Plastics	0.6%
Glass	0.1%
Textiles, leather & rubber (excl. tyres)	0.1%
Other	3.9%
Total	**100.0%**

- Drawing the initial system boundary

Based on the results in section 4.3, the initial boundary was developed. The boundary of the life cycle of C&D waste treatment and recycling begins with generation of C&D waste and ends with final disposal of waste. Figure 4.7 shows the life cycle of C&D waste, including the

C&D waste generation, waste collection and onsite sorting, pre-processing and waste processing, and recycling and disposal (including recycling, energy recovery and landfilling). Although a large part of C&D waste remains (processed intra-region), some C&D waste will be transported across regions and be processed in other regions after waste collection and onsite sorting, and some waste will be transported to other regions after pre-processing. Through processing and recycling, most C&D waste can be recycled for further production, some waste will be processed from waste to energy, and the rest disposed of in landfill.

During processing and recycling, labour resources, machinery, energy, etc. will be input to the system, while the system will output waste, products, energy and environmental pollutants. Inputs and outputs will have environmental, economic and social impacts involving cross-regional mobility of C&D waste.

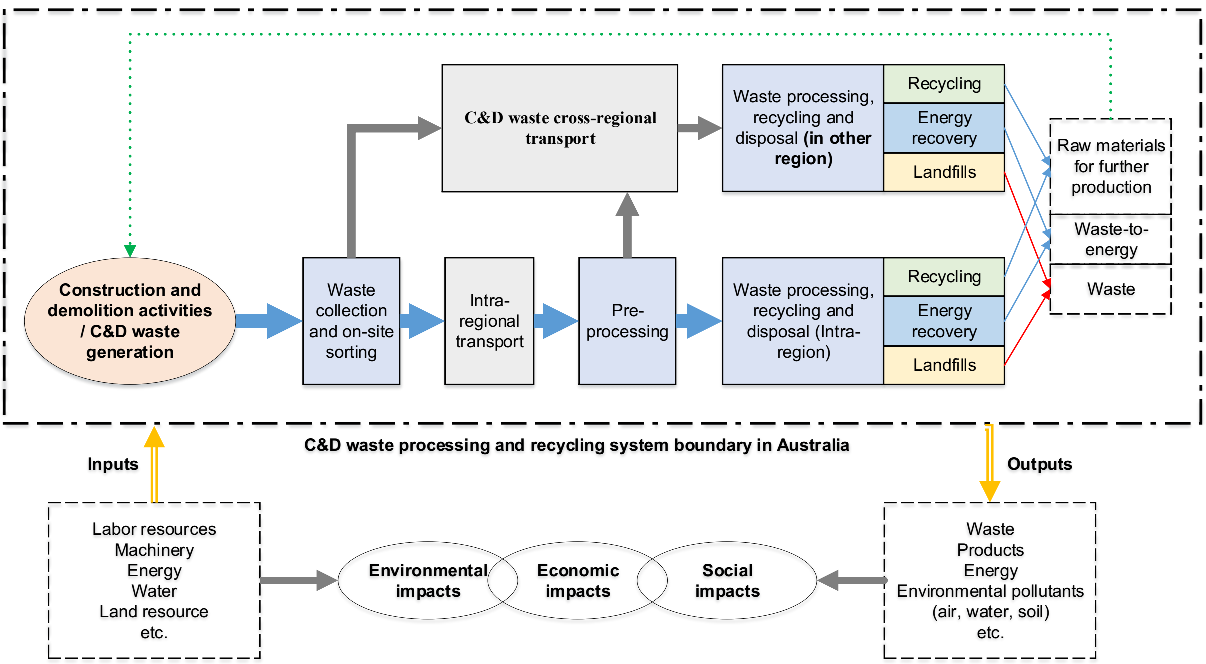


Figure 4.7: C&D waste processing and recycling system boundary

4.4.1.2 Identifying key life cycle stages and activities

Although the practice of C&D waste recycling flows varies from case to case, typical handling of C&D waste consists of several steps. Based on the results in section 4.3, life cycle stages and activities of C&D waste processing and recycling are identified as well. Life cycle stages and activities are based on current practice in Australia, which may vary slightly from other countries. For instance, although there are few reconstruction projects reusing building components from demolished buildings, the C&D waste reuse is rare in practice. Even the recycler occasionally resells bricks sorted from demolition waste to private buyers for paving garden paths. According to the definitions of reusing/recycling, the above method should considered as recycling rather than reusing, as it has changed the function of materials. Therefore, the reuse of C&D waste will not be considered as a key life cycle stage. Key stages and activities of C&D waste processing and recycling are shown in Table 4.5. Detailed in section 5.2.

Table 4.5: Key stages and activities of C&D waste processing and recycling

Key stages			Key activities
S1	C&D waste generation		Construction or demolition
S2	Waste onsite treatment	Waste collection	Collection
		Waste onsite sorting	Sorting
S3	Intra-regional transportation		Loading, transportation, unloading
S4	Waste pre-processing		Sorting, compression
S5	Cross-regional transportation		Loading, transportation, unloading
S6	Waste recycling and disposal	Recycling	Initial sorting, crushing, manually sorting, machinery sorting, cleaning, packaging
		Energy recovery	Initial sorting, crushing, waste-to-energy
		Landfilling	Landfilling

Based on key life cycle stages and activities, the LCA base model can be developed as shown in Figure 4.8.

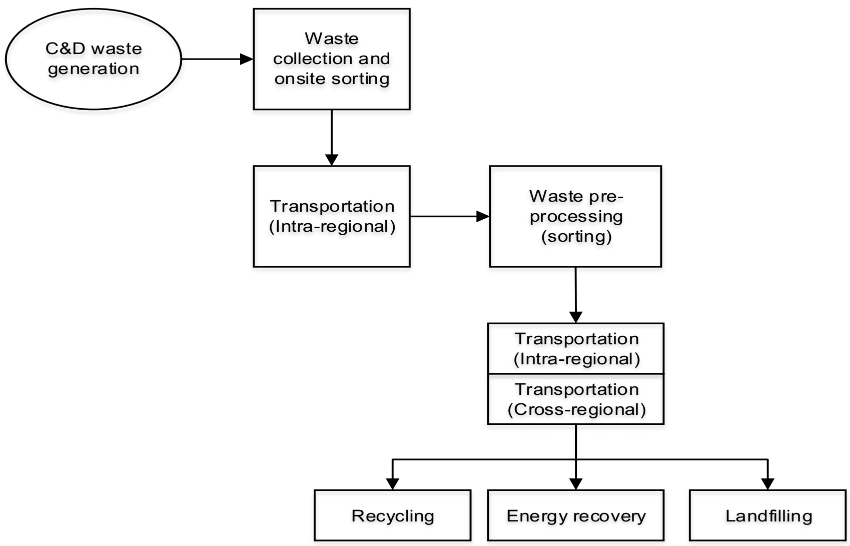


Figure 4.8: LCA-calculation base model

4.4.1.3 Identifying inputs/outputs for stage and activity

After identifying key stages and activities during the life cycle of C&D waste processing and recycling, inputs/outputs should be identified. Based on the literature review, desktop survey, site survey and expert interview detailed in section 4.3 and results in Chapter 5, inputs for a unit process of C&D waste processing and recycling can be waste (for treatment), labour resources, machinery, raw materials, energy, water, land resources, etc. Outputs can be waste, products, energy, release to the air, release to water, release to the soil, radionuclides, noise, waste heat, etc. The concept of input/outputs of a unit process is shown in Figure 4.9. Actual inputs and outputs will be discussed in section 4.4.5.

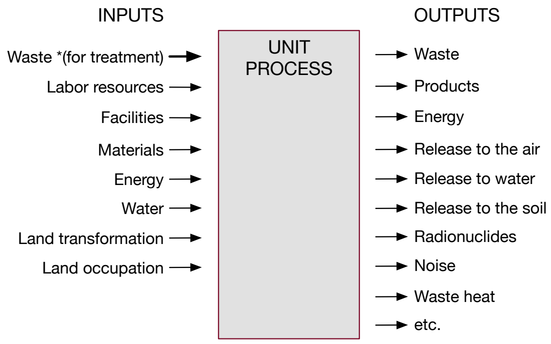


Figure 4.9: Inputs and outputs of a unit process

4.4.1.4 Identifying impact factors

As not all input/output factors can be directly used as impacts assessment indicators, some of them need to be converted via midpoint factors in assessment models. Based on the LCA principle, the input of energy is not only considered as the amount of energy used during the process, but the related impacts of production of energy. Based on identified inputs and outputs, specialised indicators for cross-regional mobility of C&D waste is proposed in this study. For instance, special development environmental impact indicators mainly focus on the setting of assessment parameters such as energy, land resources and water. The economic indicator is value (money) which includes costs and benefits during the life cycle of C&D waste processing and recycling. The social indicator is concentrated on employment, which is a key factor for social impacts in many assessment models. The concept of indicators is shown in Figure 4.10. Impact assessment methods and indicators for each dimension are discussed in more detail in sections 4.4.2 to 4.4.4. More specifically, section 4.4.2 presents environmental impacts factors, section 4.4.3 presents economic impacts factors, and section 4.4.4 presents social impacts factors.

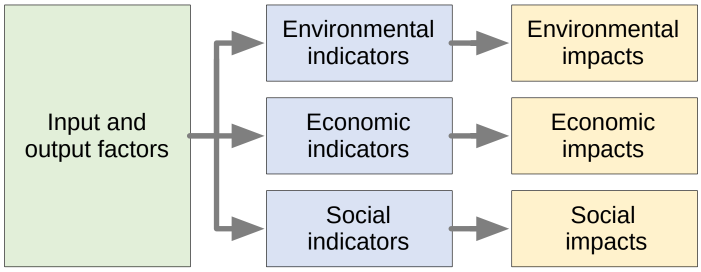


Figure 4.10: Concept of the indicators for assessment

Based on these factors, a series of Excel based calculation models were developed (available at: https://drive.google.com/open?id=1EUwj-QgWSixAm30cqV1fBQKbsCU7rBSX).

4.4.1.5 Collecting data and conducting inventory analysis

The most demanding task in performing an LCA is data collection and this is the case throughout the entire research process. The data in an LCA study consists of two parts: foreground and background data. Foreground data is used to create the modelling system, and it is normally collected from specific companies via interviews or questionnaires. Since these data may involve confidentiality and terminology issues, the willingness to provide such data sometimes depends on the relationship between researchers and data copyright owners. Although much secondary data is available in the literature or databases, it is usually found that at least a few processes or materials are unavailable (Goedkoop et al., 2008). Previous studies have developed some strategies to collect data. In terms of background data on the production of generic materials (energy and emission factors), this is usually available in databases or can be found in the literature. In most cases, an extensive literature review was essential to locate the missing data in databases (Dahlbo et al., 2015). Based on the literature review, the most popular sources for background data in C&D waste LCA studies is the *Ecoinvent* database, which has been adopted by several studies (Bohne et al., 2008; Mercante et al., 2012; Ortiz et al., 2010; Wang et al., 2018; Wu et al., 2015).

Given this information, a systematic data collection plan will developed for this study. Detailed inventory database and data collection is discussed in section 4.4.5. General data collection strategies adopted in the study are listed below.

- Firstly, key stages and activities of C&D waste treatment and recycling will be identified based on site surveys, expert interviews and expert seminars (see section 4.3.3).
- Secondly, the study will identify key resource inputs in key stages and activities involving cross-regional mobility in different scenarios, based on site surveys, expert

interviews and desktop survey (illustrated in section 4.3.3). The whole picture of the foreground data will be established via the synthesisation of information gathered from these mixed methods.

- Finally, assessment indicators and related background data in the model will be identified from databases and a desktop survey including published journal papers and open access reports. For instance, unit environmental impacts data will be collected from the eco-database *Ecoinvent (GaBi Professional)* while economic and social data will be collected from open access reports such as the *Australian Annual Statistical Report*.

4.4.1.6 Calculating and conducting scenario analysis

Scenario analysis helps to determine more suitable C&D waste management methods and to make strategical recommendations to decision makers for enhancing C&D waste management performance as a whole. Scenarios in this study are presented and discussed in section 4.4.6.

4.4.1.7 Interpreting the results

Once the above steps are finalised, the value of impact/input factors can be calculated, such as CO_2 and SO_2. However, these data are not easily understood by non-specialists. It is necessary to transfer these figures into a more understandable language such as damage to human health, damage to ecosystem diversity, damage to resource availability, and so on. As discussed in the literature review, many environmental impact assessment methods have been developed while there are few well-developed methods available for the assessments of economic and social aspects. Previous C&D waste-LCA studies normally select one well-developed impact assessment method or a refined method, rather than create impact assessment methodologies. Based on this principle, the impacts assessment methods will adopt the following strategies:

a. *Assessing environmental impacts of cross-regional mobility of C&D waste*. Environmental impacts of processing C&D waste normally consider resource inputs and impacts during the collection, transportation, processing, recycling and landfilling of waste. These resource inputs mainly include energy, raw materials, land and water; these impacts mainly include the release of SO_2, CO_2 and NO_X (Ortiz et al., 2010). The processes of conducting life cycle assessment for environmental impacts of cross-regional mobility of C&D waste will follow the standards ISO 14040 and ISO 14044 (Finkbeiner et al., 2006). As discussed in the literature review, *CML 2015* developed by the Centre of Environmental Science of Leiden University is the most recent and comprehensive environmental assessment methods available. This study will adopt environmental impacts assessment.

b. *Assessing economic impacts of cross-regional mobility of C&D waste*. Cross-regional mobility of C&D waste will change the amount of waste treated in regions involved in mobility activities, and increasing or decreasing waste treatment would directly or indirectly affect the running cost of processing waste from collection to final disposal, and further influence the benefits of selling recycled products. The study will adopt the bottom-up principle to assess economic impacts.
c. *Assessing social impacts of cross-regional mobility of C&D waste*. The whole process of treating C&D waste may have social impacts, for example, excessive working time, health and safety, human rights and community infrastructure. However, as reviewed in Chapter 3, these indicators are difficult to quantify and not widely adopted; some studies adopted a single indicator (such as job employment) to successful assess social impacts (Dreyer et al., 2006; Norris et al., 2011; Yuan, 2012). This study will adopt this strategy to assess social impacts.

Impacts assessment for each dimension is discussed in detail in sections 4.4.2 to 4.4.4.

4.4.2 Environmental impact factors and characterisation indicators

Before environmental impacts can be assessed, it is necessary to identify environmental impact factors for each material at each life cycle stage by conducting input/output analysis, and then quantify environmental impact factors using inventory analysis and calculation of characterisation indicators (see sections 4.4.2.1 and 4.4.2.2).

4.4.2.1 Environmental impact factors

Based on section 4.4.1 above, the life cycle of C&D waste undergoes various stages and activities, such as C&D waste generation, waste collection and onsite sorting, pre-processing, transportation (intra-regional/cross-regional), recycling, energy recovery and landfilling. For each stage, impact factors can differ (Table 4.6 in next page). Environmental impact factors analysis is performed following the table.

Table 4.6: Environmental impact factors for each material at each life cycle stage

Stage/activity	Illustrations	Environmental impact factor
Waste collection and onsite sorting	 **Waste collection and onsite sorting**	• Energy consumption of machinery • Emission from machinery
Pre-processing	 **Pre-processing**	• Energy consumption of machinery • Emission from machinery
Transportation	  **Intra-regional transportation** **Cross-regional transportation***	• Energy consumption of vehicles • Emission from vehicles
Waste recycling	 **Recycling aggregates**	• Environmental impacts from the operation • Environmental impacts deduction[2] of the recycled materials by replacing the use of natural materials
Energy recovery	 **Waste to energy***	• Environmental impacts from incineration • Environmental impacts deduction of waste to energy
Landfilling	 **Landfills**	• Environmental impacts from the operation • Environmental impacts from loss of recyclable materials

Note: all photos taken by the author in the site survey, except for two photos sourced from Google Image.*

[2] Environmental impacts deduction: as recycling will decrease the use of raw materials, it will reduce the environmental impacts of waste. Normally, this benefit is considered as environmental impacts deduction in LCA.

- *Waste collection and onsite sorting*

After C&D waste is generated, machinery (such as a shovel loader, mechanical claw, etc.) will be employed to collect and initially sort waste into different types. During processing, the machinery will consume energy (i.e. diesel) and release environmental pollutants. The environmental impacts of waste collection and onsite sorting mainly come from the energy consumption of machinery and emission from machinery.

- *Pre-processing*

Pre-processing at the waste station includes multiple methods and steps using machinery and labour. During processing, the main equipment includes mechanical grabs, crusher and separating conveyor, etc. The environmental impacts of waste pre-processing mainly come from energy consumption of machinery and emission from machinery during operation.

- *Transportation*

After the generation of C&D waste, the waste will be transported to the C&D waste processing station for further processing or to landfill. In some cases, waste will be transported to other regions (i.e. cross-regional mobility). During transportation, environmental impacts mainly come from energy consumption of vehicles and exhaust emission.

- *Waste recycling*

During the recycling processing, C&D waste materials will be recycled into different recycled products according to characterisation of waste composition. For instance, masonry waste is normally recycled into aggregates, while metals will be recycled to according materials (e.g., steel, aluminium, copper, etc.). For waste recycling, apart from environmental impacts from the operation, deduction of environmental impacts by replacing the use of natural materials by recycled products should be considered.

- *Energy recovery*

Some combustible C&D waste materials such as timber, plastics, paper, etc. can be utilised as an alternative fuel to be incinerated to generate energy (i.e. electricity). After considering environmental impacts during waste incineration, the generated electricity can have some environmental benefits. Hence, when calculating environmental performance of energy recovery, environmental impacts deduction of waste to energy need to be included.

- *Landfilling*

In the landfilling situation, environmental impacts are evident from two aspects: 1) operation (machinery operation and energy consumption); 2) loss of recyclable materials due waste landfill. In most cases, the recycling of C&D waste can generate environmental benefits since recycled waste materials can replace the use of natural materials.

4.4.2.2 Environmental impact characterisation indicators

Based on the systematic review of environmental impact assessment methods (see section 3.5 in Chapter 3), this study selects *CML-2015* as the base method for environmental characterisation factors. There are three main reasons for choosing to choose this method: (1) the CML series were developed by the Institute of Environmental Sciences, Leiden University, The Netherlands, which is a well-known sustainability research community; (2) the method restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties; (3) this method is the latest version of the CML series available in *GaBi Professional* software, a popular LCA software for sustainability research. Background information for CML methods can be found in the report *Handbook on Life Cycle Assessment* (Guinée & Lindeijer, 2002).

According to the *CML 2015* method regarding the baseline of characterisation models and factors, there are 12 core characterisation factors mainly used for environmental impacts, including:

- **Global Warming Potential (GWP).** Climate change is defined as the impact of human emissions on radiative forcing in the atmosphere. Most of these emissions enhance radiative forcing, causing the temperature of the earth's surface to rise. This is popularly referred to as the 'greenhouse effect'.
- **Acidification Potential (AP)**. Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). The major acidifying pollutants are SO_2, NO_X and NH_X.
- **Eutrophication Potential (EP)**. Eutrophication covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P).
- **Ozone Layer Depletion Potential (ODP)**. Ozone layer depletion refers to thinning of the stratospheric ozone layer as a result of anthropogenic emissions. It impinges on all four areas of protection: human health, the natural environment, man-made environment and natural resources.

- **Abiotic Depletion elements (ADP elements)**. Abiotic depletion potential for each extraction of minerals.
- **Abiotic Depletion fossil (ADP fossil)**. Abiotic depletion potential for each extraction of fossil fuels.
- **Freshwater Aquatic Ecotoxicity Potential (FAETP inf.)**. Freshwater aquatic ecotoxicity refers to impacts of toxic substances on freshwater ecosystems.
- **Human Toxicity Potential (HTP inf.)**. This impact category covers the impacts on human health of toxic substances present in the environment.
- **Marine Aquatic Ecotoxicity Potential (MAETP inf.)**. Marine aquatic ecotoxicity refers to impacts of toxic substances on salt water ecosystems.
- **Photochem, Ozone Creation Potential (POCP)**. Photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants.
- **Terrestic Ecotoxicity Potential (TETP inf.)**. Terrestic ecotoxicity potential covers each emission of a toxic substance to air, water, and/or soil.
- **Land Occupation (LO)**. The subcategory of land use impacts is concerned with loss of land as a resource, in the sense of being temporarily unavailable. The areas of protection are natural resources and the man-made environment.

Descriptions and explanations for these indicators are detailed in Table 4.7 in next page.

Table 4.7: Environmental impact characterisation indicators

	Indicator	Description	Explanation	Unit
EI1	GWP 100 years	Global Warming Potential	Climate change is defined have as the impact of human emissions on the radiative forcing of the atmosphere. Most of these emissions enhance radiative forcing, causing the temperature at the earth's surface to rise. This is popularly referred to as the 'greenhouse effect'.	kg CO_2-Equiv.
EI2	AP	Acidification Potential	Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). The major acidifying pollutants are SO_2, NO_X and NH_X.	kg SO_2-Equiv.
EI3	EP	Eutrophication Potential	Eutrophication covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P).	kg Phosphate-Equiv.
EI4	ODP, steady state	Ozone Layer Depletion Potential	Ozone layer depletion potential refers to thinning of the stratospheric ozone layer as a result of anthropogenic emissions. It impinges on all four areas of protection: human health, the natural environment, man-made environment and natural resources.	kg R11-Equiv.
EI5	ADP elements	Abiotic Depletion elements	Abiotic depletion potential for each extraction of minerals.	kg Sb-Equiv.
EI6	ADP fossil	Abiotic Depletion fossil	Abiotic depletion potential for each extraction of fossil fuels.	MJ
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot.	Freshwater aquatic ecotoxicity refers to impacts of toxic substances on freshwater ecosystems.	kg DCB-Equiv.
EI8	HTP inf.	Human Toxicity Potential	This impact category covers the impacts on human health of toxic substances present in the environment.	kg DCB-Equiv.
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot.	Marine aquatic ecotoxicity refers to impacts of toxic substances on salt water ecosystems.	kg DCB-Equiv.
EI10	POCP	Photochem, Ozone Creation Potential	Photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants.	kg Etheme-Equiv.
EI11	TETP inf.	Terrestic Ecotoxicity Potential	Terrestic ecotoxicity potential covers each emission of a toxic substance to air, water, and/or soil.	kg DCB-Equiv.
E12	LO	Land Occupation	The subcategory of land use impacts is concerned with loss of land as a resource, in the sense of being temporarily unavailable. The areas of protection are natural resources and the man-made environment.	m^3

Note: explanation of indicators based on the Handbook on Life Cycle Assessment: Operational guide to ISO standards (Guinée & Lindeijer, 2002)

4.4.3 Economic impacts assessment methods and indicators

As discussed in Chapter 3, unlike environmental performance assessment, there are not many well-developed methods for economic performance assessment. Although the possibility of adding economic issues to the LCA methodology has been discussed in studies such as the Life Cycle Cost Assessment, as previously mentioned, these debates are often confused and not productive (Goedkoop et al., 2008). The calculations of C&D waste treatment and processing costs were considered differently among different studies. For instance, some studies divide the cost according to the procedure of processing C&D waste, such as collection, transportation, landfilling, recycling and so on (Begum et al., 2006; Duran et al., 2006; Tam et al., 2014); some studies consider the cost of input resources, such as labour, energy, equipment, land and so on (Klang et al., 2003; Srour et al., 2013; Zhao et al., 2010) while some studies use more abstractive indicators such as investments, operational costs, treatment/disposal costs; taxes, and subsidies (Bohne et al., 2008; Gomes et al., 2008; Zhao et al., 2011).

The selection of indicators is usually conducted via literature review, questionnaire, case study, or secondary data in previous studies. As discussed in section 3.5.2, there are many difficulties in accurately assessing the economic performance of C&D waste management. Firstly, it is difficult to consider many important cost factors, such as investment, research, management expenses, and marketing in the LCA model. Secondly, these economic factors change timely, which poses challenges to model interest rates or discount rates. Thirdly, many companies invest a lot of human resources to track market prices, exchange rates and sales profits. It is unrealistic to assume that LCA experts can make improvements. Finally, economic data is usually the company's confidential business information, so it is difficult to obtain such data from public sources or through interviews with C&D waste management practitioners.

Based on the framework proposed in section 4.4.1, this study will adopt a method that combines resource input analysis and stage/activities analysis to estimate economic impacts of cross-regional mobility of C&D waste. The framework for conducting economic impacts assessment is shown in Figure 4.11.

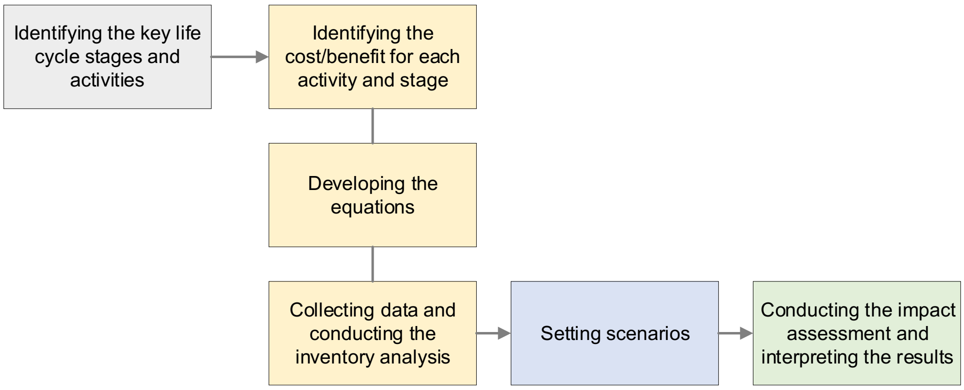


Figure 4.11: Framework for conducting economic impacts assessment

Firstly, the study will identify key stages and activities involving cross-regional mobility of C&D waste in different scenarios in Australia, according to section 4.4.1. As discussed before, construction and demolition activities generate C&D waste, collected from construction or demolition sites using C&D waste collection bins. After collection, C&D waste will be transported via tracks to the next stop, which include the C&D waste pre-processing centre, C&D waste recycling centre or landfill in intra-region or other regions.

Secondly, the study will identify key resource inputs in these key stages and activities involving cross-regional mobility in different scenarios. This aims to further calculate industry income for each activity and stage (see Figure 4.12). It is noticed that key resource inputs cannot be collected from a single data source. The whole picture will be established via synthesisation of information of these mixed methods. Data collection and data source is presented in more detail in section 4.4.5.

Finally, the indicator will be determined for economic impacts assessment of cross-regional mobility of C&D waste in Australia based on the review in Chapter 3. To make the assessment more useful and meaningful, the economic impacts indicator will adopt the concept "industry income", borrowed from GDP calculation in the statistics discipline (Mielnik & Goldernberg, 2002; Sutton et al., 2002). Industry income refers to the income of participants in the C&D waste management industry through providing services or products. As cross-regional mobility of C&D waste will directly affect the industry income for each sector taking part in C&D waste management. Such an indicator can well reflect economic impacts of cross-regional mobility of C&D waste.

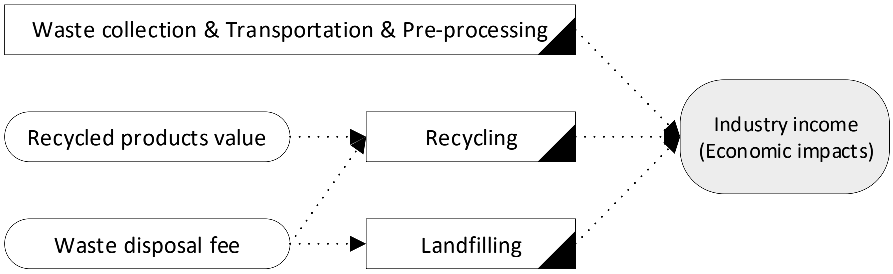


Figure 4.12: Industry income analysis framework

4.4.4 Social impacts assessment methods and indicators

As revealed in the literature review in Chapters 2 and 3, social impact assessment has attracted less attention compared to environmental and economic impact assessment. From a broader perspective, social impact assessment relates closely to different stakeholder groups throughout the life cycle of construction and demolition activities, including employees, consumers and local communities. Social impact assessment often concerns issues like wages, health and safety and access to education. However, the barriers to conducting satisfactory social impact assessment lie in the fact that issues at stake are wide-ranging and often difficult to quantify in a meaningful way (Goedkoop et al., 2008).

4.4.4.1 Overview of social impacts assessment

Since 1990s, there are discussions on conducting social impacts criteria in life cycle assessment (LCA). The wide-known publication is the Workshop Report: "*A Conceptual Framework for Life Cycle Impact Assessment*" by *Society of Environmental Toxicology and Chemistry (SETAC)* (Fava et al. 1993). The social impact category proposed in the study initiated an increasing discussion among LCA methodology developers to consider social aspects in their environmental-LCA models.

This early research was then followed by Dreyer et al. (2006), Weidema (2006) and Benoît et al. (2011). Assessment frameworks for social impact in LCA have been proposed in these studies. The frameworks mainly including impact categories, damage categories, and recommendations for category indicators and inventory data. These studies and many others (Hunkeler 2006; Hutchins & Sutherland 2008; Jørgensen et al. 2008; Klöpffer & Renner 2008; Labuschagne et al., 2005), developed methods for social life cycle assessment (SLCA), and also highlighted critical issues that needed more efforts. With the development of SLCA, there is an ISO standard namely the ISO 26000:2010, which provides general guidance instead of requirements, hence it cannot be certified as same as many other ISO standards.

In some SLCA studies (Jorgensen et al., 2008), the perception of social impacts is variable in different situations. For instance, A SLCA focusing on social impacts generated from the production process may have different direction with an assessment that concentrate on social consequences. Although it is needed to agree on the most relevant impacts in the SLCA. However, there is a lack of a common agreement about impact categories.

4.4.4.2 Indicators of social impacts assessment

Generally, SLCA is used for assessing social impacts of the complete life cycle of a product or a system. Such as natural resource extraction, processing, manufacturing, assembly, sales, use, recycling, and disposal. Benoit et al., (2010) summarised some common aspects of a SLCA, "*In some case, each of these life cycle stages can be associated with geographic locations, where one or more of these processes are carried out (mines, factories, roads, rail, harbours, shops, offices, recycling-firms, disposal sites). At each of these geographic locations, social and socio-economic impacts may be observed in five main stakeholder categories: (1) Workers/employees; (2) Local community; (3) Society (national and global); (4) Consumers (covering end-consumers as well as the consumers who are part of each step of the supply chain); and (5) Value chain actors*" (Benoit et al., 2010).

However, these indicators are difficult to quantify in a meaningful way, hence most previous studies did not apply the full set of indicators. When developing quantitative indicators, it is assumed that the categories can be directly quantified, thereby selection of appropriate indicators becomes crucial. For example, Barthel et al. (2005) proposed adopting two indicators to measure impact category "health and safety" based on statistical sources. However, statistical data on "health and safety" is normally provided at a broad industry level. It is difficult to access the data about health and safety issues for a particular chain such as C&D waste recycling in reality.

Although the selection of social indicators in prior studies is usually conducted via literature review, questionnaire, case study, or secondary data, the select indicators also show significant differences between impact category-based and stakeholder-based studies. For instance, Klang et al., (2003) focused on the worker's point of view, while some studies consider publics apart from employees (Yuan, 2012, 2013). From the impact category-based structure, Manowong (2012) selected wide-ranging indicators such as employees' health, exposure to risks, safety, gender equality, workplace diversity, fairness and so on; on the other hand, Chung and Lo

(2003) selected an abstract indicator, namely social acceptability and equity, to assess social performance of C&D waste management. Therefore, a common procedure for selection of indicators for SLCA is not yet developed.

Respect to the impacts assessment, some SLCA methods adopt midpoint indicators, while others employ endpoint indicators. This is main based on the location of indicators on the impact pathway. For instance, job creation is usually not regarded as a goal in itself, but by contributing to family income and subsequently reducing poverty, family health can be improved, which may be regarded as the ultimate goal (Yuan, 2012; Yuan et al., 2013). In this case, job creation can thus be considered a midpoint indicator.

Based on the above discussion, the core of social impacts assessment is about the stakeholders at life cycle stages, and the number of people working in the life cycle chain is the midpoint. According to Norris (2006) and Hunkeler (2006), "*a good approach is to use a single impact category as the basis for social assessment with a link to some broadly accessible generic data used as an indicator.*" Hence, the study will select employment change (including job creation and job loss) as the indicator to replicate social impacts in the assessment models. A social impacts assessment indicator framework is shown in Figure 4.13.

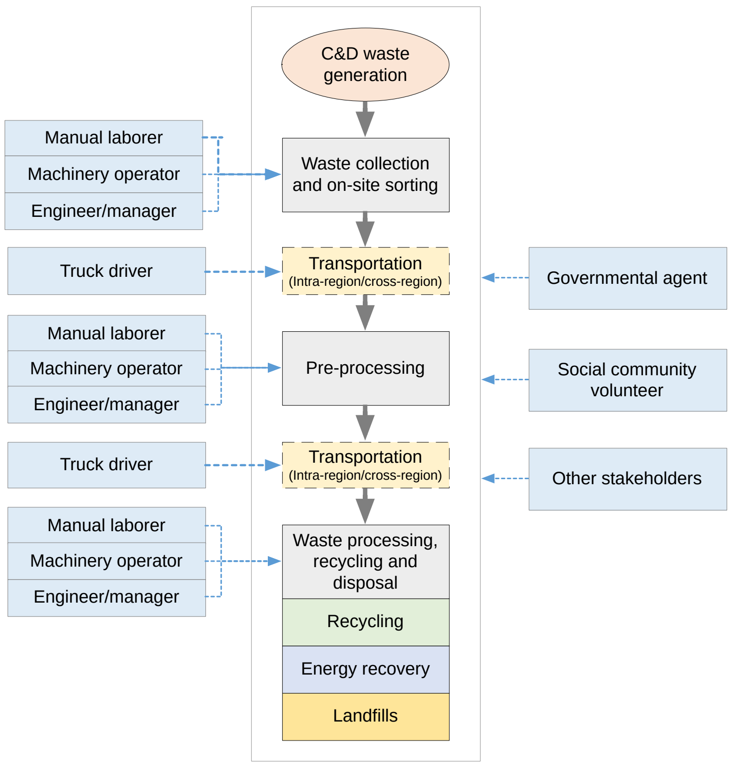


Figure 4.13: Social impacts assessment indicator framework

4.4.4.3 Calculation principle for social impacts

As cross-regional mobility of C&D waste will reduce the amount of waste being managed in regions that transport their waste to other regions, the loss of these tonnages of C&D waste could present lost opportunities for waste management service providers in original waste generation regions (SV, 2018a). Thereby, cross-regional mobility of C&D waste will affect employment in the local waste management service industry and have social impacts on communities related to the waste management industry. As discussed before, the employment impact is selected as the indicator for social impacts of C&D waste cross-regional mobility. To quantify impacts, the unit of the factor can be defined as employment in the C&D waste management industry per unit weight of managed waste (unit: p/t; where p refers to people of full-time equivalent, t refers to weight of managed C&D waste). Based on this, social impacts in terms of employment impact can be calculated by the weight of C&D waste involved in cross-regional mobility multiplied by employment impacts in the C&D waste management industry per unit weight of managed waste, as shown in the equation below.

$$SI = W \times EI$$

Where *SI* refers to social impacts of cross-regional mobility of C&D waste; W refers to the weight of C&D waste involving in the cross-regional mobility; and *EI* the employment impacts in the C&D waste management industry per unit weight of managed waste.

4.4.5 Inventory database and data collection

As discussed in section 4.4.1, inventory data includes background and foreground data. The background data includes data on environmental impacts of energy consumption (electricity, fuel, etc.), emissions from operation, environmental impacts deduction of the recycled materials by replacing the use of natural materials, etc. The foreground data includes life cycle stages and activities, machinery, vehicle, transportation distance, etc. Fundamental inventory data required in the impacts assessment are shown in Figure 4.14.

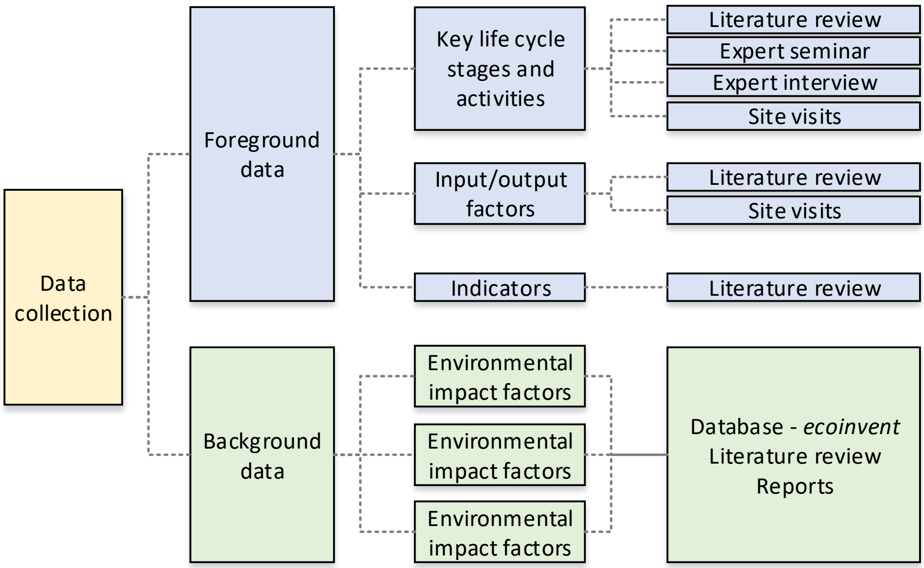


Figure 4.14: Framework for data collection

4.4.5.1 Foreground data

Apart from key life cycle stages and activities illustrated in section 4.4.1, a series of foreground data is collected for calculation. The main categories are stages, activities and resources related to C&D waste materials. Foreground data is listed in Table 4.8.

Table 4.8: Foreground data list

Category	Item	Description
Stages, activities and resources	Machinery	Main machinery used in the processing of C&D waste in each stages and activities
	Vehicle	Vehicle type used in transporting C&D waste
	Transportation distance	Transportation of intra-regional mobility and cross-regional mobility of C&D waste
	Activities	Main activities involved in collecting, processing, recycling and disposal of C&D waste
C&D related waste materials	Waste compositions	C&D waste mainly includes masonry materials (e.g. asphalt, bricks, concrete, rubble, plasterboard and cement sheeting), metals (e.g. steel, aluminium and other non-ferrous materials), organics (e.g. garden organics and timber), paper and cardboard, plastics, glass, textiles and other unclassified materials
	Waste proportion	Amount of each C&D waste composition above in 1 unit of generated C&D waste
	Replaced waste recycling materials	Materials replaced by C&D waste recycling (recycled products)

4.4.5.2 Background data – Environmental impacts assessment

The background data can be obtained from the literature review and databases. The background data include many aspects, such as energy related (e.g. electricity grid, diesel for transportation and machinery), operations (e.g. waste collection and onsite sorting, pre-processing, recycling, energy recovery and landfilling). Background datasets used in this assessment are shown in Table 4.9. In this study, environmental impact factors are exported from *GaBi Professional* software and environmental impacts characterisation indicators are calculated by the *LCIA-CML 2015* method.

Table 4.9: Background data list

Category	Item	Description
Energy	Electricity grid	Life cycle environmental impacts of 1 unit of electricity grid
	Diesel (transportation)	Life cycle environmental impacts of 1 unit of diesel per vehicle including crude oil exploration / well installation, production, transport to refining operation, transport to filling station and refuelling operation

	Diesel (machinery)	Life cycle environmental impacts of 1 unit of diesel for machinery operation including well drilling, crude oil production and processing as well as transportation of crude oil via pipeline resp. vessel to the refinery
Operations	Waste collection and onsite sorting	Environmental impacts of collecting and sorting 1 unit of C&D waste onsite
	Pre-processing	Environmental impacts of processing 1 unit of C&D waste
	Recycling	Environmental impacts and deduction of recycling 1 unit of C&D waste composition such as masonry materials, metals, organics, paper & cardboard, plastics, glass, TLR.
	Energy recovery	Environmental impacts and deduction of energy recovery of 1 unit of combustible C&D waste composition such as organics, paper & cardboard, plastics, glass, TLR.
	Landfilling	Environmental impacts of landfill of 1 unit of C&D waste

Main background data on environmental impacts assessment are presented below. The descriptions for datasets are exported from *GaBi Professional*.

- **Environmental impacts of electricity grid**

Environmental impacts of electricity grids in all states and territories in Australia (Table 4.10) are calculated via *GaBi Professional* software. As the contribution of energy sources for generating electricity in each state or territory differs, environmental impacts show dramatic differences across regions. For instance, the value of GWP 100 years for eight regions ranges from 0.295 to 1.270 kg CO_2-Equiv. for producing 1KW electricity on grid.

The dataset represents the average state-specific electricity supply for consumers, including consumption, transmission/distribution losses of low voltage electricity supply, and electricity imports from neighbouring countries or states where applicable. National specific datasets are used for power plant efficiency, combined sharing of heat and power generation (CHP) and consumption values. Data are taken from official statistics (International Energy Agency and ESAA for Australian electricity grid mixes) for the corresponding reference year. Detailed power plant models were used, which combine measured (e.g. NO_x) with calculated emission values (e.g. heavy metals). The inventory is partly based on primary industry data and secondary literature data. Detailed notes for electricity grid data in Australia are explained in *Gabi Professional*.

Table 4.10: Environmental impacts of electricity grid in Australia

	Indicators	Unit	States and Territories							
			QLD	**NT**	**SA**	**VIC**	**TAS**	**NSW**	**WA**	**ACT**
EI1	GWP 100 years	kg CO_2-Equiv.	0.949	0.645	0.718	1.270	0.295	0.948	0.744	0.947
EI2	AP	kg SO_2-Equiv.	4.64E-03	6.20E-05	1.92E-03	4.02E-03	8.69E-04	5.11E-03	3.15E-03	4.13E-03
EI3	EP	kg Phosphate-Equiv.	4.28E-04	2.31E-04	1.75E-04	2.47E-04	6.23E-05	4.12E-04	3.18E-04	3.38E-04
EI4	ODP, steady state	kg R11-Equiv.	1.05E-16	3.65E-17	2.95E-16	9.81E-16	7.73E-16	8.64E-16	9.15E-16	3.11E-16
EI5	ADP elements	kg Sb-Equiv.	8.90E-09	4.81E-09	1.22E-07	3.04E-08	1.08E-07	1.76E-08	5.38E-08	3.24E-08
EI6	ADP fossil	MJ	10.3	1.08E+01	8.70E+00	1.29E+01	3.17E+00	1.02E+01	9.63E+00	1.03E+01
EI7	FAETP inf.	kg DCB-Equiv.	5.32E-04	1.65E-03	2.44E-03	4.72E-03	1.05E-03	8.46E-04	9.40E-04	1.72E-03
EI8	HTP inf.	kg DCB-Equiv.	3.01E-02	2.02E-02	1.36E-01	3.22E-01	6.68E-02	5.71E-02	2.61E-02	1.09E-01
EI9	MAETP inf.	kg DCB-Equiv.	2.42E+01	1.43E+00	6.69E+01	1.65E+02	3.38E+01	4.01E+01	1.59E+01	6.18E+01
EI10	POCP	kg Etheme-Equiv.	2.38E-04	8.79E-05	1.12E-04	2.09E-04	4.70E-05	2.55E-04	1.73E-04	2.13E-04
EI11	TETP inf.	kg DCB-Equiv.	1.82E-04	1.46E-05	2.32E-03	5.75E-03	1.18E-03	6.68E-04	1.22E-04	1.71E-03
E12	LO	m^3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note:
Electricity grid mix 1kv-60kv
Environmental impacts are calculated by GaBi Professional software by adopting the LCIA-CML 2015 method.

- **Environmental impacts of diesel in transportation and operation**

Based on the software calculation by adopting the LCIA-CML 2015 method, environmental impacts of diesel for transportation and operation are shown in Table 4.11. The results show environmental impacts are significantly different. For instance, the GWP 100 years indicator of diesel for transportation is 0.262 kg CO_2-Equiv., while diesel used for operating machinery is 0.188 kg CO_2-Equiv.

Table 4.11: Background data on environmental impacts of diesel

	Indicator	Description [Unit]	Diesel (transportation)	Diesel (machinery)
EI1	GWP 100 years	Global Warming Potential [kg CO2-Equiv.]	0.262	0.188
EI2	AP	Acidification Potential [kg SO2-Equiv.]	2.47E-03	1.74E-03
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	2.68E-04	1.53E-04
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	4.05E-15	9.17E-16
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	5.14E-08	5.39E-08
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	4.66E+01	4.55E+01
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	7.95E-03	6.48E-03
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	4.77E-02	3.96E-02
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	3.17E+01	2.60E+01
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	2.72E-04	2.55E-04
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	3.80E-04	2.64E-04
E12	LO	Land Occupation [m^3]	N/A	N/A

Note: Environmental impacts are calculated by Software: GaBi Professional by adopting LCIA-CML 2015 method.

The dataset for diesel covers the entire supply chain of diesel products for transportation and machinery. This includes well drilling, crude oil production and processing, transportation of crude oil via pipeline resp. vessel to the refinery as well as transportation from the refinery to the filling station. Main technologies such as conventional (primary, secondary, tertiary) and unconventional (oil sands, in-situ) production, include parameters such as energy consumption, transport distances and crude oil processing technologies. The dataset represents national / regional consumption mix (supply mix) including domestic production and imports. The biogenic components blended with fossil fuels are also modelled individually. The inventory is mainly based on industry data and it is completed, where necessary, using secondary data. Detailed notes for the data on environmental impacts of diesel are shown in *GaBi Professional*.

- **Environmental impacts of pre-processing 1 kg of C&D waste**

Initial treatment of C&D waste is pre-processing (i.e. sorting the waste into different category according to its compositions for further processing such as recycling, energy recovery, or landfilling). Based on the software calculation, the environmental impacts of pre-processing 1 kg of C&D waste are shown in Table 4.12. All relevant background data such as energy and auxiliary material are taken from the GaBi databases, maintaining consistency. Detailed notes for the data are shown in *Gabi Professional*.

Table 4.12: Environmental impacts of pre-processing 1kg of C&D waste

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	2.69E-03
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	1.81E-05
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	4.43E-06
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	6.08E-16
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	3.59E-09
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	5.06E-02
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	2.03E-05
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	2.35E-04
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	1.09E-01
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	1.98E-06
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	4.99E-06
E12	LO	Land Occupation [m^3]	N/A

Note: Construction waste processing (EN15804 C3) (DE), production mix, at plant,1kg. Environmental impacts are calculated using GaBi Professional by adopting the LCIA-CML 2015 method.

- **Environmental impacts of landfilling 1 kg of inert C&D waste**

Based on the software calculation, the environmental impacts of landfilling 1kg of inert C&D waste are shown in Table 4.13. The dataset covers all relevant process steps / technologies for the treatment of waste in landfill. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. All relevant background data such as energy and auxiliary material are taken from the GaBi databases, maintaining consistency. Detailed notes for the data on environmental impacts of landfilling 1 kg of inert C&D waste are shown in *GaBi Professional*.

Table 4.13: Environmental impacts of landfilling 1kg inert C&D waste

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	1.59E-02
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	9.42E-05
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	1.30E-05
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	3.55E-15
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	6.13E-09
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	2.06E-01
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	7.17E-05
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	1.01E-03
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	3.42E+00
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	7.32E-06
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	3.87E-04
E12	LO	Land Occupation [m^3]	4.04E-04

Note: Construction waste processing (EN15804 C3)(DE), production mix, at plant,1kg. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

- **Environmental impacts of recycling 1kg of masonry waste**

Based on the software calculation, environmental impacts of recycling 1kg of masonry waste are shown in Table 4.14. As the recycling of masonry waste (recycled aggregates) can replace the use of raw materials such as stone and sand, the calculation has considered the environmental impacts deduction of recycling.

Table 4.14: Background data on recycling masonry waste

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	0.02
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	7.89E-05
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	6.82E-06
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	3.68E-15
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	1.64E-09
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	2.11E-01
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	1.90E-04
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	6.14E-03
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	3.28E+00
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	6.65E-06
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	1.49E-04
E12	LO	Land Occupation [m^3]	2.08E-05

Note: Crushed stone grain 2-15 mm (production mix, at plant) (CN). Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The dataset covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. The LCA of stone chips covers the process of limestone extraction in the quarry, cleaning, two stages of crushing, drying and the organisation of production. System boundaries are represented by the finished product stone chips (dried) at the factory gate. Transports from the factory to the building site are not considered and must be included according to the system boundaries. All relevant background data such as energy and auxiliary material are taken from the *GaBi* databases, maintaining consistency. Detailed notes for the data on environmental impacts/benefits of recycling masonry waste are shown in *GaBi Professional*.

- **Environmental impacts of recycling 1kg of steel**

Based on the software calculation, environmental impacts of recycling 1kg steel are shown in Table 4.15. As the recycling of steel can replace the use of raw materials such as secondary steel scrap, the calculation has considered the environmental impacts deduction of recycling.

Table 4.15: Background data on recycling steel

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-1.51E+03
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-3.61E+00
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-9.97E-02
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	4.83E-05
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-5.27E-04
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-1.60E+04
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	2.08E+00
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-1.01E+02
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-2.70E+05
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-7.73E-01
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	8.09E-01
E12	LO	Land Occupation [m^3]	4.17E-04

Note: *Steel scrap (AU-OneSteel) – Credit/burden for production/use of recycled steel. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.*

The dataset covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. This dataset is based on primary data from internationally adopted production processes, linked to regional precursor chains. Detailed notes for the data on environmental impacts of recycling steel are shown in *GaBi Professional*.

- **Environmental impacts of recycling 1kg of aluminium**

Based on the software calculation, environmental impacts of recycling 1kg of aluminium are shown in Table 4.16. As the recycling of aluminium can replace the use of raw materials, such as secondary aluminium ingot, the calculation has considered the environmental impacts deduction of recycling.

Table 4.16: Background data on recycling aluminium

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-672
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-2.08E+00
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-1.48E-01
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-8.49E-08
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-5.16E-04
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-9.65E+03
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-2.58E+00
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-5.31E+02
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-1.40E+06
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-1.46E-01
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-9.18E-01
E12	LO	Land Occupation [m^3]	6.21E-06

Note: Secondary aluminium ingot, 97% recycling efficiency, recycled aluminium (RNA). Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The dataset covers all relevant process steps and technologies over the supply chain of the represented cradle-to-gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. LCI modelling is fully consistent. Detailed notes for the data of the environmental impacts of recycling aluminium are shown in *Gabi Professional*.

- **Environmental impacts of recycling 1 kg copper**

Based on the software calculation, environmental impacts of recycling 1kg of copper are shown in Table 4.17. As the recycling of copper can replace the use of raw materials, such as secondary copper, the calculation has considered the environmental impacts deduction of recycling.

Table 4.17: Background data on recycling copper

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-3.06
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-5.62E-02
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-1.17E-03
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	3.22E-14
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-2.63E-03
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-3.00E+01
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-1.10E-01
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-5.66E+00
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-2.29E+03
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-2.43E-03
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-2.99E-02
E12	LO	Land Occupation [m^3]	6.21E-06

Note: Cleaning, smelting and refining, 95% primary metal content to recycling, 5% to landfill. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The dataset covers all relevant process steps / technologies over the supply chain of the represented partly aggregated cradle to gate inventory with good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. This dataset is based on primary data from internationally adopted production processes, linked to regional precursor chains. LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of recycling copper are shown in *GaBi Professional*.

- **Environmental impacts of landfilling 1kg of metal**

Environmental impacts of landfilling 1kg of metal use the data on landfilling 1kg inert C&D waste are shown in Table 4.13 above.

- **Environmental impacts of recycling 1kg of timber**

Based on the software calculation, environmental impacts of recycling 1kg timber are shown in Table 4.18. As the recycling of timber can replace the use of raw materials such as woodchips, the calculation has considered the environmental impacts deduction of recycling.

Table 4.18: Background data on recycling of timber

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-35.7
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-6.43E-01
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-1.23E-01
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-4.31E-10
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-2.67E-06
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-3.76E+02
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-5.26E-01
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-2.02E+01
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-2.01E-05
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-1.18E-01
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-6.69E-01
E12	LO	Land Occupation [m^3]	4.17E-05

Note: Timber (AU) Recycling of hardwood timber, kiln-dried, rough-sawn, untreated (EN 15804 D) -- hardwood reprocessing, end-of-life mix, at producer, 784 kg/m3 at 12% moisture content (dry basis) / 10.7% water content (wet basis). Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The datasets consider shredding and effectively down-cycling into woodchips. Wood waste is chipped and assigned credits relative to the production of woodchips from virgin softwood, which should be avoided. The sequestered CO2 and energy content of the timber are assumed to retain the system boundary so that future product systems can also claim these credits without double counting. LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of recycling timber in Australia are shown in *GaBi Professional*.

- **Environmental impacts of energy recovery 1 kg timber**

Based on the software calculation, environmental impacts/benefits of recovering 1kg timber are shown in Table 4.19. As the energy recovery of timber can generate energy, the calculation has considered the environmental impacts deduction of waste to energy.

Table 4.19: Background data on energy recovery of timber

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-1.29E-03
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-1.27E+00
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-2.55E-01
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-2.54E-10
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-1.34E-07
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-1.03E+02

EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-4.98E-02
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-4.06E+00
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-1.23E+02
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-1.35E-01
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-3.94E-02
EI12	LO	Land Occupation [m^3]	4.17E-05

Note: Timber (AU)Energy recovery from hardwood timber, kiln-dried, rough-sawn, untreated (EN 15804 C3)-end-of-life mix, at producer, 784 kg/m3 at 12% moisture content (dry basis) / 10.7% water content (wet basis). Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

Energy recovery includes the preparation of woodchips (chipping and drying to 12% moisture content (MC), depending on initial MC). The woodchips are then used as a fuel to power a combined heat and power plant with an overall efficiency of 80% (40% heat, 40% electricity). LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of energy recovery of timber are shown in *GaBi Professional*.

- **Environmental impacts of landfilling 1kg of timber**

Based on the software calculation, environmental impacts of landfilling 1kg timber are shown in Table 4.20. LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of landfilling timber are shown in *GaBi Professional*.

Table 4.20: Background data on landfilling of timber

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	1.04E+03
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	2.54E-01
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	4.08E-02
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	5.29E-10
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	1.13E-05
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	8.53E+02
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	1.87E-01
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	2.51E+00
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	5.59E-03
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	2.07E-01
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	6.18E-01
EI12	LO	Land Occupation [m^3]	8.33E-04

Note: Timber (AU) landfill of hardwood timber, kiln-dried, rough-sawn, untreated (NGA) (EN 15804 C4)-end-of-life mix, at producer, 784 kg/m3 at 12% moisture content (dry basis) / 10.7% water content (wet basis). Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

This dataset has been prepared in accordance with ISO 14025:2006, EN 15804:2013, PCR 2012:01 of the International EPD System (2015) and the General Programme Instructions of the Australasian EPD® Programme (Version 1.0, 2015). It is an end-of-life scenario (EN 15804 modules) which has a degradable organic carbon fraction (DOCF) wood value of 0.1%. This is based on bioreactor laboratory research by Wang et al. (2011) on blackbutt timber, one of the dominant hardwood species in Australia. This value can be considered as an upper limit for degradation of carbon in solid timber placed in landfill. The impacts associated with landfill are declared in module C4. All landfill gas that is combusted for energy recovery (module C4) is assumed to occur in a power plant with an electrical conversion efficiency of 36%, and the resulting electricity receives a credit for offsetting average electricity from the Australian grid (module D) on line. Detailed notes for the data on environmental impacts of recycling cardboard are shown in *GaBi Professional*.

- **Environmental impacts of recycling 1kg of cardboard**

Based on the software calculation, environmental impacts/benefits of recycling 1kg of cardboard are shown in Table 4.21. The dataset covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of recycling cardboard are shown in *GaBi Professional*.

Table 4.21: Background data on recycling cardboard

	Indicator	**Description [Unit]**	**Value**
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-2.19E+00
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-4.45E-03
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-1.06E-03
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-1.25E-12
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-1.65E-04
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-3.23E+01
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-8.65E-03
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-1.40E-01
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-8.35E+01
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-4.19E-04
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-5.81E-03
EI12	LO	Land Occupation [m^3]	3.62E-04

Note: CN Gypsum cardboard agg ts stones and elements 2017/1/1 gypsum extraction and cardboard manufacturing production mix, at plant|10 kg/m2. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

- **Environmental impacts of energy recovery of 1kg of cardboard**

Based on the software calculation, environmental impacts/benefits of incinerating 1kg of cardboard are shown in Table 4.22. As the energy recovery of cardboard can generated energy, the calculation has considered environmental impacts deduction of waste to energy.

Table 4.22: Background data on waste energy recovery cardboard

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-1.42E+03
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-2.97E-01
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-5.58E-02
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-3.97E-10
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-2.79E-05
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-3.79E+02
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-6.32E-02
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-1.64E+00
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-1.48E-03
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-1.97E-02
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-3.42E-02
EI12	LO	Land Occupation [m^3]	3.62E-04

Note: EU-28 Paper / Cardboard in waste incineration plant p-agg ts Incineration 2017/1/1 waste-to-energy plant with dry flue gas treatment, without collection, transport and pre-treatment/production mix (region specific plants), at plant|15.0 MJ/kg net calorific value. Environmental impacts calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The dataset covers all relevant process steps for thermal treatment and corresponding processes, such as disposal of air pollution control residues or metal recycling. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. The system is partly terminated (open outputs, electricity and steam). Electricity and steam flow has to be connected and adapted to local specificities in order to take into account these credits. Credits for recovered metals are already included. Detailed notes for the data on environmental impacts of recycling cardboard are shown in *GaBi Professional*.

- **Environmental impacts of landfilling 1kg of cardboard**

Environmental impacts of landfilling 1kg of metal using the data of landfilling 1kg timber waste are shown in Table 4.20 above.

- **Environmental impacts of recycling 1kg of plastics**

Based on the software calculation, environmental impacts of recycling 1kg of plastics are shown in Table 4.23. As the recycling of plastics can replace the use of raw materials such as secondary plastics, the calculation has considered environmental impacts deduction of recycling.

Table 4.23: Background data on recycling plastics

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-0.672
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-6.62E-04
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-9.31E-05
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-7.68E-13
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-1.60E-07
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-3.77E+00
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-5.93E-04
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-2.23E-02
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-2.55E+01
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-4.50E-05
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-2.40E-04
EI12	LO	Land Occupation [m^3]	3.33E-05

Note: Plastics (EU28) plastics granulate secondary -plastics granulate secondary (low metal contamination), from post-consumer plastics waste, via grinding, metal separation, washing, palletisation. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The dataset covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. This dataset is based on primary data from internationally adopted production processes, linked to regional precursor chains. All relevant background data such as energy and auxiliary material are taken from the GaBi databases, maintaining consistency. Detailed notes for the data on environmental impacts of recycling plastics are shown in *GaBi Professional*.

- **Environmental impacts of energy recovery of 1kg of plastics**

Based on the software calculation, environmental impacts/benefits of incinerating 1kg of plastics are shown in Table 4.24. As the energy recovery of plastics can generated energy, the calculation has considered the environmental impacts deduction of waste to energy.

Table 4.24: Background data on waste incineration of plastics

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	1.740
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-6.20E-04
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-2.98E-05
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-2.54E-08
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	3.00E-06
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-1.40E+00
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	9.17E-04
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-3.35E-02
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-5.59E+02
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-5.97E-05
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	1.23E-04
EI12	LO	Land Occupation [m^3]	3.33E-05

Note: Plastics (EU28) Waste incineration of plastics (rigid PVC)-average European waste-to-energy plant, without collection, transport and pre-treatment. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The dataset covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. The transfer coefficients for the elements (used to allocate different elements and substances to different mediums including air, bottom ash and air pollution control residues and energy and utility consumption of waste-to-energy plants are determined based on industry data (real plant data) and a comprehensive literature research. LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of energy recovery of plastics are shown in *GaBi Professional*.

- **Environmental impacts of landfilling 1kg of plastics**

Based on the software calculation, environmental impacts of landfilling 1kg of plastics are shown in Table 4.25. The dataset covers all relevant process steps / technologies for the treatment of waste in landfill. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of landfilling plastics are shown in *GaBi Professional*.

Table 4.25: Background data on plastics waste in landfill

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	0.0702
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	1.92E-04
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	1.96E-04
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	1.90E-14
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	1.54E-08
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	1.02E+00
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	3.24E-04
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	3.93E-03
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	6.98E+00
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	2.10E-05
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	1.39E-03
EI12	LO	Land Occupation [m^3]	6.67E-04

Note: Plastics (EU28) Plastics waste on landfill-landfill including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment. Landfill height 30 m, landfill area 40.000 sqm. Environmental impacts calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

- **Environmental impacts of recycling 1kg of glass**

Based on the software, environmental impacts of recycling 1kg of plastics are shown in Table 4.26. As the recycling of glass can replace the use of raw materials, such as secondary glass, the calculation has considered environmental impacts deduction of recycling.

Table 4.26: Background data on glass recycling

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-8.25
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-6.77E-02
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-6.98E-03
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-3.53E-12
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-2.20E-05
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-9.76E+01
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-4.26E-01
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-3.66E+01
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-1.63E-04
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-8.05E-02
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-4.43E-02
EI12	LO	Land Occupation [m^3]	2.00E-05

Note: Glass (EU28) Window glass sample-production mix, at plant, 7,5 kg/m2. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The LCA of the filling material includes the production of 1kg of window glass without frame. The system boundary is the product at the factory gate. Transport from the factory to the construction site is not taken into account and has to be incorporated in a system approach, if necessary. All relevant background data such as energy and auxiliary material are taken from the GaBi databases, maintaining consistency. Detailed notes for the data on environmental impacts of recycling glass are shown in *GaBi Professional*.

- **Environmental impacts of landfilling 1kg of glass**

Based on the software calculation, environmental impacts of landfilling 1kg of glass are shown in Table 4.27. The dataset covers all relevant process steps / technologies for the treatment of waste in landfill. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. LCI modelling is fully consistent. Detailed notes for the data on environmental impacts of landfilling glass are shown in *GaBi Professional*.

Table 4.27: Background data on glass in landfill

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	0.0159
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	9.42E-05
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	1.30E-05
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	3.60E-15
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	6.11E-09
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	2.06E-01
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	7.17E-05
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	1.01E-03
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	3.42E+00
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	7.32E-06
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	3.87E-04
EI12	LO	Land Occupation [m^3]	4.00E-04

Note: Glass (EU28) Inert matter (Glass) on landfill-landfill including leachate treatment and without collection, transport and pre-treatment, Landfill height 30 m, landfill area 40.000 sqm. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

- **Environmental impacts of recycling 1kg of TLR (rubber)**

Based on the software calculation, environmental impacts of recycling 1kg of rubber are shown in Table 4.28. As the recycling of rubber can replace the use of raw materials, the calculation has considered environmental impacts deduction of recycling.

Table 4.28: Background data on TLR recycling

	Indicator	Description [Unit]	Value
EI1	GWP 100 years	Global Warming Potential [kg CO_2-Equiv.]	-1.31E+01
EI2	AP	Acidification Potential [kg SO_2-Equiv.]	-2.76E-02
EI3	EP	Eutrophication potential [kg Phosphate-Equiv.]	-4.39E-03
EI4	ODP, steady state	Ozone Layer Depletion Potential [kg R11-Equiv.]	-7.48E-11
EI5	ADP elements	Abiotic Depletion elements [kg Sb-Equiv.]	-2.22E-04
EI6	ADP fossil	Abiotic Depletion fossil [MJ]	-2.45E+02
EI7	FAETP inf.	Freshwater Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-4.37E-01
EI8	HTP inf.	Human Toxicity Potential [kg DCB-Equiv.]	-6.18E-01
EI9	MAETP inf.	Marine Aquatic Ecotoxicity Pot. [kg DCB-Equiv.]	-9.89E+02
EI10	POCP	Photochem, Ozone Creation Potential [kg Etheme-Equiv.]	-3.43E-03
EI11	TETP inf.	Terrestic Ecotoxicity Potential [kg DCB-Equiv.]	-2.56E-01
EI12	LO	Land Occupation [m^3]	3.29E-05

Note: Glass (EU28) Window glass sample-production mix, at plant, 7,5 kg/m2. Environmental impacts are calculated using GaBi Professional software by adopting the LCIA-CML 2015 method.

The LCA of the filling material includes the production of 1kg of window glass without frame. The system boundary is the product at the factory gate. Transport from the factory to the construction site is not taken into account and has to be incorporated in a system approach if necessary. All relevant background data such as energy and auxiliary material are taken from the GaBi databases, maintaining consistency. Detailed notes for the data on environmental impacts of recycling glass are shown in *GaBi Professional*.

- **Environmental impacts of energy recovery of 1kg of TLR**

Environmental impacts of energy recovery of 1kg of TLR use the average value of energy recovery of timber, cardboard and plastics.

- **Environmental impacts of landfilling 1kg of TLR**

Environmental impacts of landfilling 1kg of TLR use the data on landfilling 1kg of timber C&D waste are shown in Table 4.21 above.

- **Environmental impacts of recycling 1kg of other unclassified waste**

Environmental impacts of recycling 1kg of other unclassified waste use the average value of recycling all C&D waste materials.

- **Environmental impacts of energy recovery 1 kg other unclassified waste**

The environmental impacts of energy recovery of 1kg of other unclassified waste use the average value of energy recovery of timber, cardboard, plastics and TLR.

- **Environmental impacts of landfilling 1kg of other unclassified waste**

Environmental impacts of landfilling 1kg of other unclassified waste use the average value of landfilling all C&D waste materials.

4.4.5.3 Background data – economic impacts assessment

Based on the industry expert survey and desktop survey, the background data on economic impacts assessment is detailed in Table 4.29.

Table 4.29: Background data on economic impacts assessment

Activities/Waste materials	**Recycled products**	**Value**	**Unit**	**Source**
Waste collection & transportation & pre-processing	Initially sorted waste	0.18	AUD/kg	Expert survey
Waste types	**Recycled products**	**Value**	**Unit**	**Source**
Masonry material	Recycled aggregate	18	AUD/t	Expert survey
Steel	Steel scrap	500	AUD/t	Expert survey
Aluminium	Aluminium scrap	2,000	AUD/t	Expert survey
Copper	Copper scrap	1,000	AUD/t	Expert survey
Organics (Timber)	Woodchips	100	AUD/t	Expert survey
Paper & Cardboard	Paper & Cardboard	100	AUD/t	Expert survey
Plastics	Plastics	100	AUD/t	Expert survey
Glass	Glass	20	AUD/t	Expert survey
TLR	N/A	0	AUD/t	-
Others	N/A	Average	AUD/t	-
Disposal fee	N/A	100*	AUD/t	Desktop survey
Landfilling	Disposal fee	100	AUD/t	-
Recycling	Disposal fee plus recycled products selling	-	AUD/t	-

Note: Assume that intra-regional transportation and cross-regional transportation are equal to the fee. The disposal fee is based on the average of national data.

4.4.5.4 Background data – social impacts assessment

The background data on social impacts assessment are the data on employment for managing one ton of C&D waste. According to the *National Waste Report 2018 (*p. 55) (Dee, 2018), "the Australian waste and resource recovery sector managed about 55 Mt of waste in 2016--17, including about 32 Mt through recycling and most of the rest through landfills. Based on a major report for the department, the value of the sector's activities in 2014--15 was about $15.5

billion, comprising $12.6 billion from service provision and $2.9 billion from the sale of recovered materials (CIE 2017). The value added by waste-related activities was $6.9 billion, accounting for 0.43% of Australian gross domestic product (GDP). The sector directly employed almost 50,000 people (full-time equivalent), accounting for about 0.5% of total employment". Based on the data, the employment per ton of C&D waste can be calculated by dividing 50,000 people (full-time equivalent) by 55 Mt, which equates to 0.00091 people (full-time equivalent) per ton of managed C&D waste (p/t).

4.4.6 Scenario setting and main assumptions

As discussed before, there are a number of options for treating generated C&D waste. For instance, collected waste can be transported cross-regionally to be processed in other regions (e.g. recycling, energy recovery and landfill); waste can also be treated and disposed of intra-regionally. To identify C&D waste management options with the lowest impact, the study has developed three main scenario settings: Scenario 0.0 (Base scenario); Scenario setting I (cross-regional mobility +, recycling rate +, landfilling rate -), and Scenario setting II (cross-regional mobility + , landfilling rate +, recycling rate -) for testing how the impacts change according to different cross-regional mobility situations and waste treatment methods.

There are two main assumptions in the study. The impacts assessment is conducted using calculation and scenario analysis. Firstly, it is assumed that treatment methods and efficiency are identical in states/territories. As the aim of the study is to assess the impacts of cross-regional mobility of C&D waste in Australia, the entire country is regarded as the objective when considering impacts assessment. Secondly, consistent recycling rate and cross-regional mobility rates are adopted for all waste materials and regions when conducting scenario analysis. C&D waste contains multiple waste compositions and as Australia contains multiple regions, it is impossible to set up specific recycling rates for each waste material and region. Nor is it possible to set up specific cross-regional mobility rates for each material and region in the scenario analysis. In doing so, scenarios will be in the thousands. For instance, if the scenario setting considers four aspects (waste compositions, regions, cross-regional mobility rate and recycling rate), the number of scenarios will be 4,000=10 (number of waste compositions) ×8 (number of regions in Australia) ×5 (number of cross-regional mobility rate settings) ×5 (number of recycling rate settings) ×2 (scenario series), which is far beyond the capacity of the calculation model. Therefore, when setting up scenario I and scenario II, consistent recycling rates and cross-regional mobility rates are adopted for all waste materials and regions.

- *Scenario 0.0*

Scenario 0.0 is developed as the base-scenario based on current practice, extracted from the results in section 4.3 (see Chapter 5). In this scenario, there are six treatment options for C&D waste materials, including intra-regional recycling, cross-regional recycling, intra-regional energy recovery, cross-regional recovery, intra-regional landfilling and cross-regional landfilling. If the treatment method is not applicable to a certain material, the rate of treatment will be allocated as 0%. Figure 4.15 and Table 4.30 show the allocation of waste materials for Scenario 0.0.

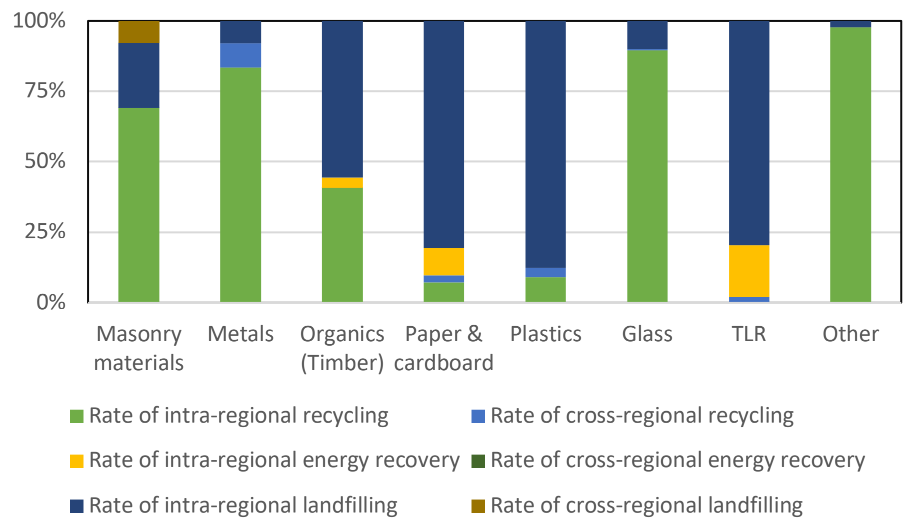


Figure 4.15: Scenario 0.0 setting

Overall, 69.2% of managed waste is recycled intra-regionally, 0.6% of managed waste is recycled cross-regionally, 0.2% of managed waste is energy recovered intra-regionally, non-managed waste is energy recovered cross-regionally, 23.6% of managed waste is landfilled intra-regionally, and 6.4% of managed waste is landfilled cross-regionally. For each waste material, the rates for treatment options vary, as follows:

- For masonry materials, accounting for 83.4% of total generated C&D waste by weight, about 69.2% of the waste is recycled intra-regionally; 0% of the waste is recycled cross-regionally; 0% of the waste is energy recovered intra-regionally; 0% of the waste is energy recovered cross-regionally; 23.2% of the waste is landfill intra-regionally; 7.6% of the waste is landfill cross-regionally.
- For metals, accounting for 6.5% of total generated C&D waste by weight, about 83.5% of the waste is recycled intra-regionally; 8.6% of the waste is recycled cross-regionally; 0% of the waste is energy recovered intra-regionally; 0% of the waste is energy

recovered cross-regionally; 7.9% of the waste is landfill intra-regionally; 0% of the waste is landfill cross-regionally.

- For organics (timber), accounting for 4.9% of total generated C&D waste by weight, about 40.8% of the waste is recycled intra-regionally; 0.1% of the waste is recycled cross-regionally; 3.5% of the waste is energy recovered intra-regionally; 0% of the waste is energy recovered cross-regionally; 55.6% of the waste is landfill intra-regionally; 0% of the waste is landfill cross-regionally.
- For paper and cardboard, accounting for 0.5% of total generated C&D waste by weight, about 7.1% of the waste is recycled intra-regionally; 2.6% of the waste is recycled cross-regionally; 9.7% of the waste is energy recovered intra-regionally; 0% of the waste is energy recovered cross-regionally; 80.6% of the waste is landfill intra-regionally; 0% of the waste is landfill cross-regionally.
- For plastics, accounting for 0.6% of total generated C&D waste by weight, about 9.1% of the waste is recycled intra-regionally; 3.3% of the waste is recycled cross-regionally; 0% of the waste is energy recovered intra-regionally; 0% of the waste is energy recovered cross-regionally; 87.6% of the waste is landfill intra-regionally; 0% of the waste is landfill cross-regionally.
- For glass, accounting for 0.1% of total generated C&D waste by weight, about 89.6% of the waste is recycled intra-regionally; 0.5% of the waste is recycled cross-regionally; 0% of the waste is energy recovered intra-regionally; 0% of the waste is energy recovered cross-regionally; 9.9% of the waste is landfill intra-regionally; 0% of the waste is landfill cross-regionally.
- For TLR, accounting for 0.1% of total generated C&D waste by weight, about 0% of the waste is recycled intra-regionally; 2.0% of the waste is recycled cross-regionally; 18.4% of the waste is energy recovered intra-regionally; 0% of the waste is energy recovered cross-regionally; 79.6% of the waste is landfill intra-regionally; 0% of the waste is landfill cross-regionally.
- For other unclassified waste, accounting for 3.9% of total generated C&D waste by weight, about 97.7% of the waste is recycled intra-regionally; 0% of the waste is recycled cross-regionally; 0% of the waste is energy recovered intra-regionally; 0% of the waste is energy recovered cross-regionally; 2.3% of the waste is landfill intra-regionally; 0% of the waste is landfill cross-regionally.

Table 4.30: Scenario 0.0 – base scenario (by weight)

Waste category	Percentage in total	Rate of intra-regional recycling	Rate of cross-regional recycling	Rate of intra-regional energy recovery	Rate of cross-regional energy recovery	Rate of intra-regional landfilling	Rate of cross-regional landfilling	total
Masonry materials	83.4%	69.2%	0.0%	0.0%	0.0%	23.2%	7.6%	100.0%
Metals	6.5%	83.5%	8.6%	0.0%	0.0%	7.9%	0.0%	100.0%
Organics (timber)	4.9%	40.8%	0.1%	3.5%	0.0%	55.6%	0.0%	100.0%
Paper & cardboard	0.5%	7.1%	2.6%	9.7%	0.0%	80.6%	0.0%	100.0%
Plastics	0.6%	9.1%	3.3%	0.0%	0.0%	87.6%	0.0%	100.0%
Glass	0.1%	89.6%	0.5%	0.0%	0.0%	9.9%	0.0%	100.0%
TLR	0.1%	0.0%	2.0%	18.4%	0.0%	79.6%	0.0%	100.0%
Other	3.9%	97.7%	0.0%	0.0%	0.0%	2.3%	0.0%	100.0%
Total	**100.0%**	**69.2%**	**0.6%**	**0.2%**	**0.0%**	**23.6%**	**6.4%**	100.0%

- *Scenario setting I*

Scenario setting I for treatment and disposal options does not consider energy recovery, but considers recycling and landfilling. This is mainly due to two reasons: firstly, there is no cross-regional mobility of C&D waste for energy recovery based on the results of this investigation (section 4.3); secondly, the amount of C&D waste materials for energy recovery is negligible, and it has been evaluated in scenario 0.0. In scenario setting I, there are 25 scenarios (i.e. scenario 1.1 to scenario 1.25) developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, the recycling rate will be increased every 25% from 0% to 95% while the landfilling rate will be decreased from 100% to 5% accordingly. The percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%.

For instance, in scenario 1.1, cross-regional mobility rate is 0%; intra-regional mobility rate is 100%; recycling rate is 0%; energy recovery rate is 0%; and landfilling rate is 100%. In scenario 1.2, cross-regional mobility rate is 25%; intra-regional mobility rate is 75%; recycling rate is 0%; energy recovery rate is 0%; and landfilling rate is 100%. Similarly, in scenario 1.25, cross-regional mobility rate is 100%; intra-regional mobility rate is 0%; recycling rate is 95%; energy recovery rate is 0%; and landfilling rate is 5%. Scenario setting I is detailed in Table 4.31.

Table 4.31: Scenario setting I

Scenario setting I (cross-regional mobility +, recycling rate +, landfilling rate -)		0%	25%	50%	75%	100%	**Cross-regional mobility**
		100%	75%	50%	25%	0%	**Intra-regional mobility**
0%	100%	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	
25%	75%	Scenario 1.6	Scenario 1.7	Scenario 1.8	Scenario 1.9	Scenario 1.10	
50%	50%	Scenario 1.11	Scenario 1.12	Scenario 1.13	Scenario 1.14	Scenario 1.15	
75%	25%	Scenario 1.16	Scenario 1.17	Scenario 1.18	Scenario 1.19	Scenario 1.20	
95%	5%	Scenario 1.21	Scenario 1.22	Scenario 1.23	Scenario 1.24	Scenario 1.25	
Recycling rate	**Landfilling rate**						

- *Scenario setting II*

Scenario setting II for treatment and disposal options considers recycling and landfilling, but does not consider energy recovery due to the same reasons explained above for scenario setting I. In scenario setting II, there are 25 scenarios (i.e. scenario 2.1 to scenario 2.25) developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, with the increased percentage of cross-regional mobility, the recycling rate will be decreased every 25% from 95% to 0% while the landfilling rate will be increased from 5% to 100% accordingly.

For instance, in scenario 2.1, cross-regional mobility rate is 0%; intra-regional mobility rate is 100%; recycling rate is 95%; energy recovery rate is 0%; and landfilling rate is 5%. In scenario 2.2, cross-regional mobility rate is 25%; intra-regional mobility rate is 75%; recycling rate is 95%; energy recovery rate is 0%; and landfilling rate is 5%. Similarly, In scenario 2.25, cross-regional mobility rate is 100%; intra-regional mobility rate is 0%; recycling rate is 5%; energy recovery rate is 0%; and landfilling rate is 95%. Scenario setting II is detailed in Table 4.32.

Table 4.32: Scenario setting II

Scenario setting II (cross-regional mobility +, recycling rate -, landfilling rate +)		0%	25%	50%	75%	100%	**Cross-regional mobility**
		100%	75%	50%	25%	0%	**Intra-regional mobility**
95%	5%	Scenario 2.1	Scenario 2.2	Scenario 2.3	Scenario 2.4	Scenario 2.5	
75%	25%	Scenario 2.6	Scenario 2.7	Scenario 2.8	Scenario 2.9	Scenario 2.10	
50%	50%	Scenario 2.11	Scenario 2.12	Scenario 2.13	Scenario 2.14	Scenario 2.15	
25%	75%	Scenario 2.16	Scenario 2.17	Scenario 2.18	Scenario 2.19	Scenario 2.20	
5%	95%	Scenario 2.21	Scenario 2.22	Scenario 2.23	Scenario 2.24	Scenario 2.25	
Recycling rate	**Landfilling rate**						

4.5 Developing optimisation strategies for C&D waste cross-regional mobility

To complete this development of optimisation strategies, a Scenario Analysis Method (see section 4.4) will be employed in this study. The principle is fairly simple: the Australian C&D waste cross-regional mobility network developed here will illustrate a series of potential scenarios for treating C&D waste; the well-established impacts assessment model will then provide methods to assess performance for each scenario in the network. Based on these results, optimisation strategies for each scenario will be recommended (see discussion in Chapter 7).

4.6 Summary

This chapter illustrated methodologies and methods that applied to this study. Multiple aspects include the research framework, investigation of management and cross-regional mobility of C&D waste, development of impacts assessment models for C&D waste cross-regional mobility, and development of optimisation strategies for managing C&D waste cross-regional mobility in Australia.

Chapter 5. Results: Part 1

5.1 Introduction

This chapter illustrates the results for RQ 1— What are the current status of cross-regional mobility of C&D waste in Australia? The results are based on the methods reported in section 4.3 in Chapter 4. The contents include two main parts. Section 5.2 will report management status of C&D waste in Australia, including compositions and generation, and fates and flows of C&D waste. Section 5.3 will present the results of C&D waste cross-regional mobility. It was found that three main types of C&D waste cross-regional mobility in Australia (i.e. transporting C&D waste interstate for recycling, transporting C&D waste interstate for landfill, and transporting C&D waste overseas for reprocessing/recycling). **The contents of this chapter have been published in associated publication 1 listed on page xiii**. The results will be fully presented in the following sections.

5.2 Management status of C&D waste in Australia

As stated in Chapter 1, C&D waste has become the most significant sold waste stream and many countries seek to increase the recycling rate of waste. With a 91% recycling rate of C&D waste in South Australia, overall the recycling rate of C&D waste in Australia has reached about 67%, which is much higher than most countries worldwide. The Australian experience in managing C&D waste could provide valuable information for other countries seeking to improve their waste management levels. By employing site survey, expert interview, expert seminar, and desktop survey detailed in section 4.2, the study is conducted in order to understand C&D waste treatment and management, particularly in relation to cross-regional mobility of waste in Australia. Firstly, the study investigates the compositions and generation of C&D waste in Australia, and provides strategies for managing waste; secondly, the study maps fates and flows of C&D waste in Australia; and thirdly, the study generates a cross-regional mobility map of C&D waste in Australia, which reveals significant information such as states and territories involved in cross-regional mobility, mobility routes and transported materials in relation to C&D waste. Based on this approach, the study also discusses characterisation of C&D waste in Australia and analyses the causes of cross-regional mobility of C&D waste (see Section 7.2). The findings will gain inside knowledge of C&D waste management in Australia, which is valuable for other countries or regions to improve their waste management performance. The study will also expand the boundary of C&D waste management theory by considering the cross-regional mobility waste issue.

5.2.1 Compositions and generation of C&D waste in Australia

5.2.1.1 C&D waste compositions in Australia

According to the definition of C&D waste in the *National Waste Report 2018*, C&D waste refers to waste produced by construction and demolition activities, including building, road and rail construction, and maintenance and excavation of land associated with construction activities. C&D waste mainly includes masonry materials (e.g. asphalt, bricks, concrete, rubble, plasterboard and cement sheeting), metals (e.g. steel, aluminium and other non-ferrous materials), organics (e.g. garden organics and timber), paper and cardboard, plastics, glass, textiles and other unclassified materials. Table 5.1 shows the main C&D waste materials identified in Australia. Some examples of C&D waste materials are also shown in Figure 5.1.

Table 5.1: Main C&D waste materials in Australia

Waste category	Waste type	Description
Masonry waste materials	Asphalt	Roadwork
	Bricks	-
	Concrete	-
	Rubble	Including non-hazard foundry sands
	Plasterboard & cement sheeting	-
Metals	Steel	Steel reinforcing, scrap steel
	Aluminium	Aluminium frames, scraps
	Non-ferrous metals	Excluding aluminium
Organics	Garden organics	-
	Timber	Raw, treated or painted timber
Paper & cardboard	Paper and cardboard	-
Plastics	Plastics	PVC piping
Glass	Glass	Glass windows, doors
Textiles, leather and rubber (TLR)	Textiles, leather and rubber	Fibreglass insulation, carpet, underlay
Other	Other unclassified materials	Any waste that contains more than one waste type

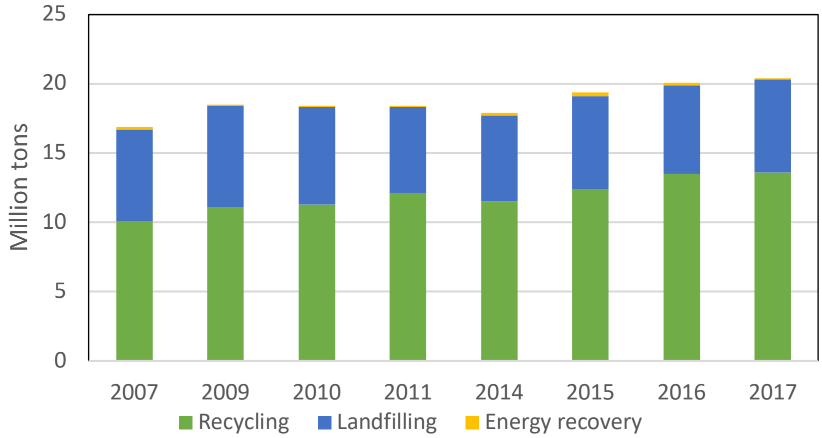
Note: All photos taken by the author during surveys of construction sites in Adelaide

Figure 5.1: Main C&D waste materials

5.2.1.2 C&D waste generation in Australia

Based on the data extracted from the *National Waste Report 2018,* C&D waste generated in 2017 is 20.4 million tons, which includes about 13.6 million tons of recycled waste, about 6.7 million tons of waste disposed in landfill, and about 0.1 million tons of energy recovered waste. As shown in Figure 5.2, the generation of C&D waste has increased steadily over the last decade from about 17 million tons in 2007 to more than 20 million tons in 2016 and 2017. The data in Figure 5.2 can be found in Table A-5.1 in Appendix B. The amount of recycled waste also increased in the survey period. From the perspective of percentages, more than 60% of

C&D waste in Australia has been recycled and around 40% was sent to landfill, where some minor materials have been energy recovered. Recycling rates of C&D waste in Australia show an increasing trend, which has increased steadily from 60% in 2007 to 67% in 2017.



Source: Data extracted from the National Waste Report 2018 (Dee, 2018)

Figure 5.2: Generation and fates of C&D waste in Australia, 2006--07 to 2016--17

Regarding the compositions of C&D waste in Australia by weight, about 83% is masonry materials, 6% metal and 5% organics waste (mainly timber). The percentages by weight of such as plastics, paper and cardboard, glass, textiles, leather and rubber are not significant, contributing less than 1% each. The remains of some 4% of total waste is waste that cannot be sorted or classified (see Figure 5.3).

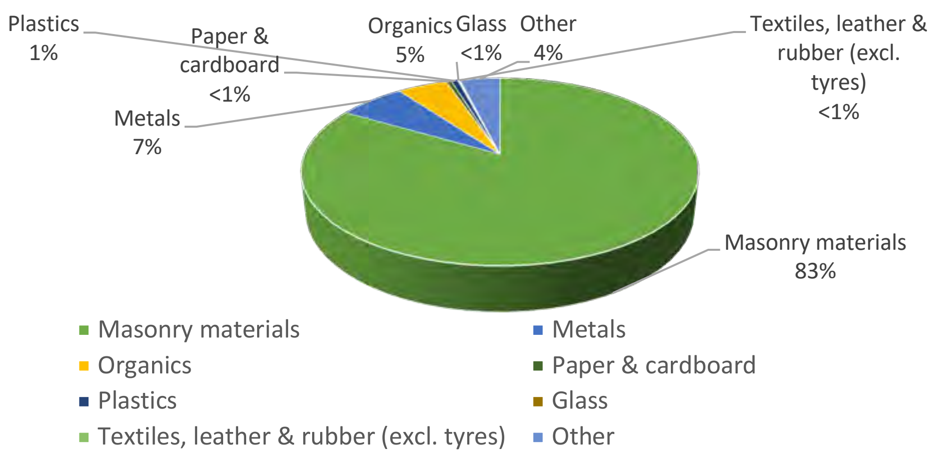
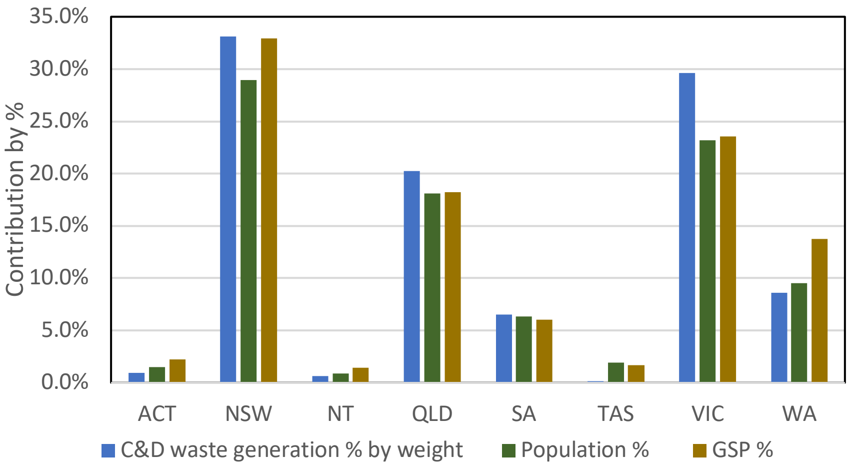


Figure 5.3: Compositions of C&D waste in Australia in 2017 (by weight)

Figure 5.4 illustrates the relationship between C&D waste generation, population and economic activity by state and territory in Australia. The data in Figure 5.4 can be found in Table A-5.2 in Appendix B. The results show NSW contributed the most C&D waste (about 33% of the total C&D waste generated in Australia in 2017). VIC contributed nearly 30% and QLD contributed about 20% of total C&D waste generation. VIC, QLD, WA and SA dominated waste generation from second to fifth place respectively. Overall, the trend of waste generation is consistent with population and economic activity, namely the state or territory with a larger population and greater economic scale normally generates more C&D waste due to more construction and demolition projects. However, waste generation contributions in NSW, VIC and QLD are significantly higher than the population percentage. One explanation could be the real estate boom in these states in recent years.



GSP refers to Gross State Product

Source: Data extracted from Australia National Waste Report 2018 (Dee, 2018)

Figure 5.4: Australian C&D waste generation, population and economic activity (by state and territory in 2017)

5.2.2 Fates and flows of C&D waste in Australia

5.2.2.1 Fates of C&D waste in Australia

Regarding the fates of C&D waste compositions in Australia, about 90% of metals have been recycled, followed by about 80% glass and 70% masonry materials recycled. According to managers interviewed in recycling centres, 95% of recyclable waste can be recycled if waste materials have been distributed into recycling facilities; however, a considerable amount of C&D waste has been transported to landfill. Hence, although recycling rates of C&D waste such as masonry materials, metals and glass are competitively high, there are significant percentages of some waste compositions being transported to landfill, such as organics, paper and cardboard, plastics, textiles and leather and rubber. The overall percentage of energy recovered C&D waste is minor (see Figure 5.5).

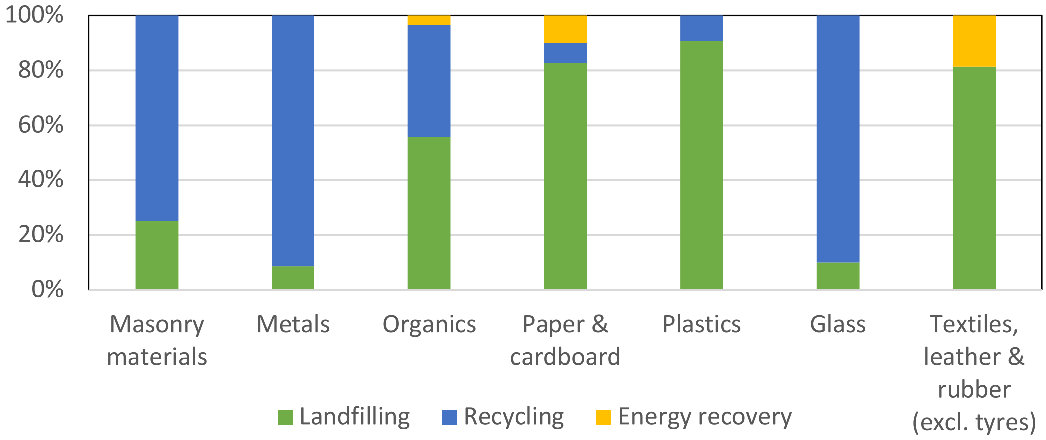


Figure 5.5: Compositions and fates of C&D waste in Australia in 2017

Based on the data extracted and processed from the *National Waste Report 2018* (Dee, 2018), Table 5.2 details the treatment of C&D waste by category in Australia. As the recycling data for each waste type in the ACT, NT and TAS are not available, the sum total of the quantity of recycling, recycling and energy recovery in this figure does not equal total waste generation. It can however indicate that C&D waste compositions sent to energy recovery are organics (mainly timber), paper and cardboard, and textiles, leather and rubber.

Table 5.2: Waste treatment by waste category in Australia in 2017

Waste category	**Landfilling** (,000 tons)	**Recycling*** (,000 tons)	**Energy recovery** (,000 tons)
Masonry materials	3908	11679	0
Metals	105	1111	0
Organics (mainly timber)	505	371	32
Paper & cardboard	74	7	9
Plastics	110	11	0
Glass	2	14	0
Textiles, leather & rubber (excl. tyres)	20	0	5
Other	17	711	0
Total	**4740**	**13903**	**46**

Note:
-- The data is extracted and processed from the National Waste Report 2018 (Dee, 2019).
-- The sum total of the quantity of recycling and energy recovery in this figure does not equal total waste generation, as the recycling data for each waste type in the ACT, NT and TAS are not available.
-- The recycling data for QLD is processed from Recycling and Waste in Queensland 2018 (QG, 2018).

5.2.2.2 Flows of C&D waste in Australia

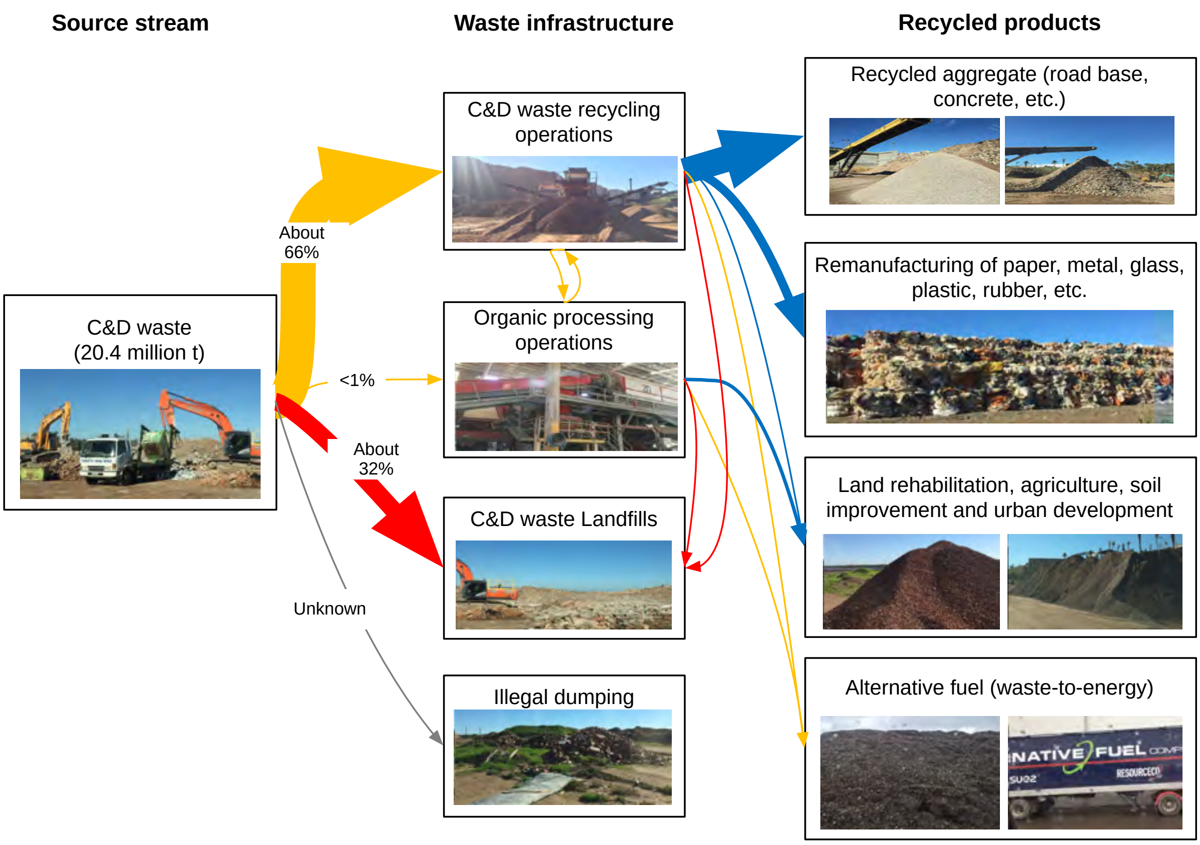
Regarding the fates of C&D waste compositions in Australia, about 90% of metals have been recycled, followed by 80% glass and 70% masonry materials. According to the senior manager of a renowned C&D waste recycler 1 in SA in the expert interview (detailed in section 4.3.3) "*95% of recyclable waste can be recycled if the waste materials have been distributed into the recycling facilities; however, there is a considerable amount of C&D waste that has been transported to landfill.*" Hence, although the recycling rates of C&D waste such as masonry materials, metals and glass are competitively high, there are significant percentages of some waste compositions being transported to landfill, such as organics, paper and cardboard, plastics, textiles, leather and rubber. The overall percentage of C&D waste that is energy recovered is minor.

Based on the compositions and fates of C&D waste data extracted and processed from the *National Waste Report 2018* (Dee, 2018), site surveys of two "C&D waste recycling centres" in SA and interviews with "senior managers" of two renowned C&D waste recyclers in SA (detailed in section 4.3.3), C&D waste flows in Australia are detailed in Table 5.3. A diagram for C&D waste flows in Australia is developed in Figure 5.6. This figure shows three main C&D waste infrastructure types including waste recycling operations, organic processing operations and landfills. Apart from such C&D waste infrastructure, some C&D waste is still being dumped illegally, according to the "senior manager of renowned C&D waste recycler 1 and 2 in SA", consistent with the information revealed in the *National Waste Report 2018* (Dee, 2018).

Table 5.3: C&D waste flows in Australia

Source stream	**Percentage**	**Waste infrastructure**	**Percentage**	**Recycled products**
C&D waste	100%	C&D waste recycling operations	66%	Recycled aggregate (road base)
				Remanufacturing of paper, metal, glass, plastics, rubber, etc.
		Organic processing operations	<1%	Land rehabilitation, agriculture, soil improvement and urban development
				Alternative fuel (waste-to-energy)
		C&D waste landfill	32%	-
		Illegal dumping	<1%	-

Note:
- Recycled products of land rehabilitation, agriculture, soil improvement and urban development, and alternative fuel (waste-to-energy) are also produced from C&D waste recycling operations.
- Data extracted from the National Waste Report 2018 (Dee, 2018).



Note:

- All pictures were taken by the author during site surveys in Adelaide.

- Waste flow data were extracted and processed from the National Waste Report 2018 (Dee, 2018).

- The waste flow diagram was refined with the help of a manager of a renowned SA C&D waste recycler.

Figure 5.6: C&D waste flows in Australia

After waste recycling operations, the majority of masonry waste is recycled into aggregates mainly for road base, concrete, etc. Some waste compositions such as metal, paper, glass and plastics have been sorted and classified for further remanufacturing. Some combustible waste compositions such as organics (mainly timber), paper and cardboard, and textiles, leather and rubber (excl. tyres) can be made into alternative fuel for energy recovery (i.e. waste-to-energy). Some waste components can be used for land rehabilitation, soil improvement and urban development. Some sorted organic compositions will be sent to organic processing operations and the remainder of unrecyclable waste disposed of in landfill.

Some organic C&D waste materials such as timber and garden waste are transported to organic processing operations directly from construction or demolition sites. In organic processing operations, the waste will be used for land rehabilitation, soil improvement and urban development, and some combustible waste can be made into alternative fuel for energy recovery. Unrecyclable waste materials will be disposed of in landfill. While in some situations, some recyclable waste materials sorted in organic processing operations will be transported to waste recycling operations.

5.2.2.3 The life cycle procedure of C&D waste

Although the practice of C&D waste recycling flows varies from case to case, the typical process of handling C&D waste consists of several steps. Based on the expert seminar, expert interviews and site visits, key life cycle stages and activities of C&D waste processing and recycling were identified.

Generally, after C&D waste generation, the waste will be collected and initially sorted onsite via waste bins and then transported to C&D waste processing facilities, where waste will be sorted into different categories. Once waste is sorted and classified, there are numbers of options to treat and dispose of waste, including recycling, energy recovery and landfill.

In some cases, generated C&D waste will be transported to C&D waste recycling centres directly from construction and demolition sites. In the C&D waste recycling centre, the waste is processed and disposed of according to compositions and classifications of waste. In other cases, generated C&D waste will be sorted onsite, and some unrecyclable waste will be transported to landfill, while recyclable waste will be transported to the pre-processing station or recycling centre. In practice, the main jobs of the pre-processing station are sorting and compression. The processed waste will be transported to the recycling centre or sold to waste-material buyers.

Due to lack of facilities, lower disposal fees, or shorter transportation distance, some C&D waste will be transported to other regions for further processing, which leads to cross-regional mobility of C&D waste. A typical flow map for stages and activities of C&D waste processing and recycling with cross-regional mobility is illustrated in Figure 5.7 (see next page).

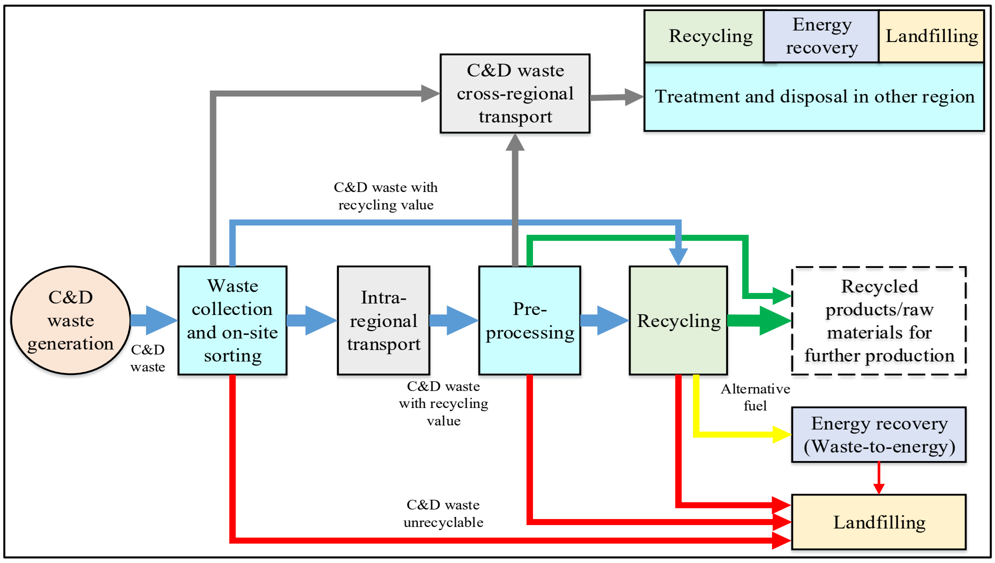


Figure 5.7: Key life cycle stages and activities of C&D waste (with cross-regional mobility)

5.3 C&D waste cross-regional mobility in Australia

Although the majority of C&D waste by weight is processed within the region, it is found that some of the waste is generated in one state but transferred to another (Dee, 2018). Typically, the *National Waste Report 2018* and states/territories only report that waste is managed within their boundaries; but based on the in-depth desktop survey (detailed in section 4.3.2), some cross-regional mobility of C&D waste can be revealed. There are three main forms of waste cross-regional mobility in Australia (i.e. transported interstate for recycling, transported interstate for landfill, and exported overseas for reprocessing/recycling). Normally, recyclable materials after reprocessing will be further recycled. A map is developed to illustrate cross-regional mobility of waste in Australia (see Figure 5.8). The data used in the map is detailed in Table 5.4.

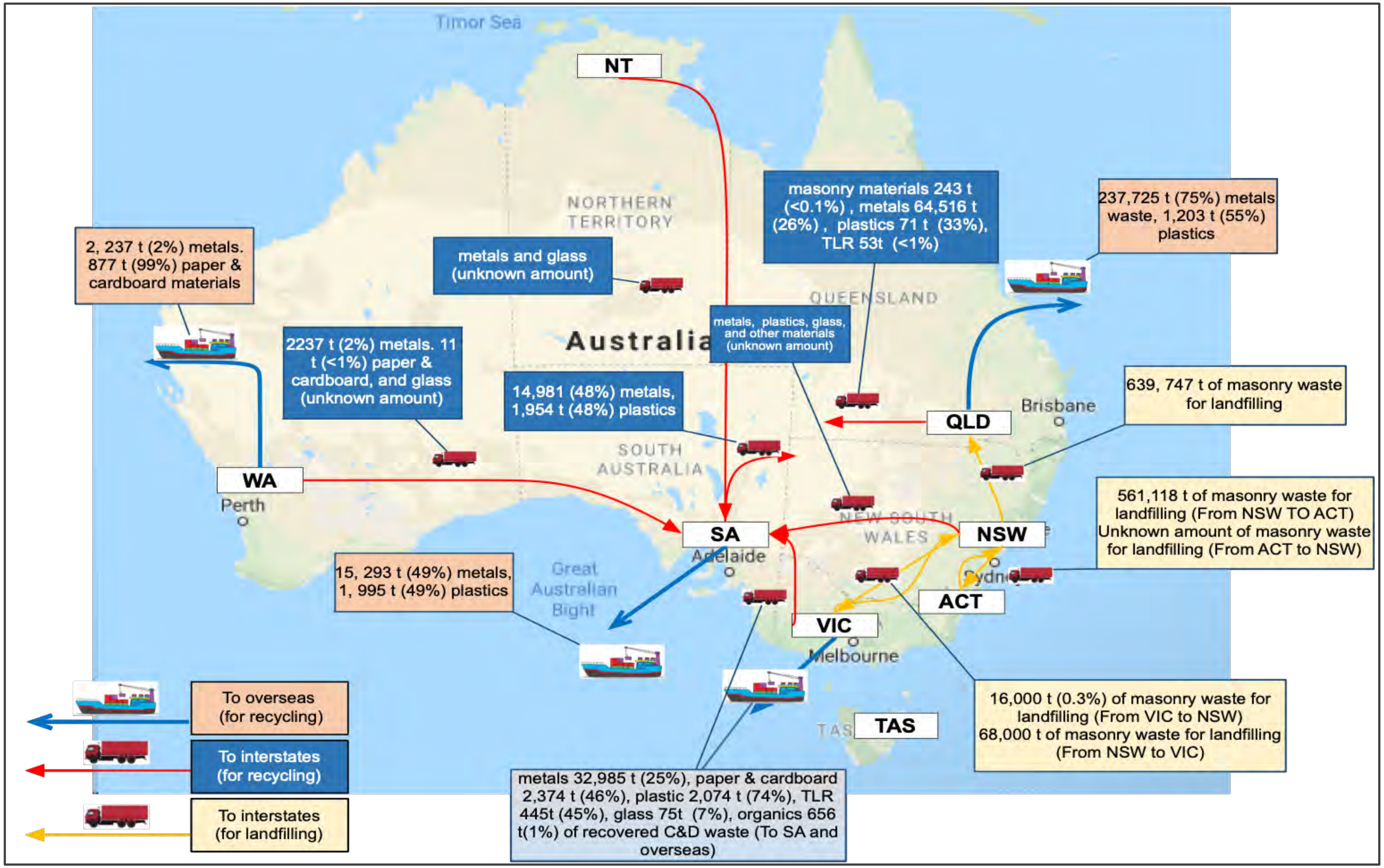


Figure 5.8: C&D waste cross-regional mobility map of Australia

Table 5.4: Australian C&D waste cross-regional mobility

Origin	Destination	C&D waste materials	Treatment and disposal	Notes
Interstate cross-regional mobility				
VIC	NSW	Masonry waste 16,000 t (0.3%)	Landfilling	Cross-border and export flows data extracted from *State-wide Waste and Resource Recovery Infrastructure Plan* (Victoria 2017); (SV, 2018a) Waste generation data source: *Victorian Recycling industry Annual Report 2015--16 (SV, 2017)*, *Victorian Recycling industry Annual Report 2016--17 (SV, 2018b)*; *South Australia's Recycling Activity Survey 2017--18 Report (GISA, 2019)*
VIC	Interstate (SA) or overseas	Metals 32,985 t (25%), paper & cardboard 2,374 t (46%), plastics 2,074 t (74%), TLR 445t (45%), glass 75t (7%), organics 656 t (1%) of recovered C&D waste	Reprocessing (recycling)	
NSW	VIC	68,000 tons of masonry waste	Landfilling	
NSW	ACT	561,118 t of masonry waste	Landfilling	Queanbeyan landfill waste went to the ACT; *National Waste Report 2018* (Dee, 2018)
ACT	NSW	Masonry waste (unknown)	Landfilling	ACT landfill waste sent to levy-free landfill in NSW; *National Waste Report 2018, p. 84* (Dee, 2018)
NSW	QLD	Masonry waste 639, 747 t	Landfilling	*National Waste Report 2018, p. 84* (Dee, 2018)
QLD	Interstate	Masonry materials 243 t (<0.1%) , metals 64,516 t (26%) , plastics 71 t (33%), TLR 53t (<1%) of recovered C&D waste	Reprocessing (recycling)	C&D waste generation data from the *National Waste Report 2018* (Dee, 2018); Other data from the *Recycling and Waste in Queensland 2018* (QG, 2018)
SA	Interstate	14,981 (48%) metals, 1,954 t (48%) plastics	Reprocessing (recycling)	Generation data from *National Waste Report 2018* (Dee, 2018); other data from *South Australia's Recycling Activity Survey 2017--18 (GISA, 2019)*
NT	SA	Metals and glass (unknown amount)	Reprocessing (recycling)	*South Australia's Recycling Activity Survey 2017--18 Report (GISA, 2019)*
NSW	SA	Metals, plastics, glass, and other materials (unknown amount)	Reprocessing (recycling)	*South Australia's Recycling Activity Survey 2017--18 Report (GISA, 2019)*
WA	SA	2,237 t (2%) metals. 11 t (<1%) paper & cardboard, and glass (unknown amount)	Reprocessing (recycling)	Generation data from the *National Waste Report 2018* (Dee, 2018); other data source: *Recycling Activity in Western Australia 2016--2017 (Waste Authority WA, 2018)*

To overseas				
VIC	Interstate (SA) or overseas	Metals 32,985 t (25%), paper & cardboard 2,374 t (46%), plastics 2,074 t (74%), TLR 445t (45), glass 75t (7%), organics 656 t(1%) of recovered C&D waste	Reprocessing (recycling)	Cross-border and export flows data extracted from *State-wide Waste and Resource Recovery Infrastructure Plan* (Victoria 2017) (SV, 2018a); Waste generation data source: *Victorian Recycling industry Annual Report 2015 – 16 (SV, 2017)*, *Victorian Recycling industry Annual Report 2016 - 17 (SV, 2018b)*; *South Australia's Recycling Activity Survey 2017-18 Report (GISA, 2019)*
QLD	Overseas	237,725 t (75%) metals waste, 1,203 t (55%) plastics	Reprocessing (recycling)	C&D waste generation data from the *National Waste Report 2018* (Dee, 2018); other data from the *Recycling and Waste in Queensland 2018* (QG, 2018)
SA	Overseas	15,293 t (49%) metals, 1, 995 t (49%) plastics	Reprocessing (recycling)	Generation data from the *National Waste Report 2018 (Dee, 2018);* other data from *South Australia's Recycling Activity Survey 2017--18 (GISA, 2019)*
WA	Overseas	2,237 t (2%) metals. 877 t (99%) paper & cardboard materials	Reprocessing (recycling)	Generation data from *National Waste Report 2018 (Dee, 2018)*; other data from *Recycling Activity in Western Australia 2016--2017 (Waste Authority WA, 2018)*

Note: Normally, recyclable materials after reprocessing will be further recycled.

5.3.1 Transporting C&D waste interstate for recycling

The results show that South Australia (SA) is at the centre of waste cross-regional mobility for reprocessing/recycling in Australia. Many states or territories transport their waste to SA for reprocessing/recycling. For instance, South Australia receives some metals and glass from the Northern Territory. It receives metals, plastics and glass from New South Wales. Apart from this, the state also received about 2,237 tons of metals (2%). 11 tons of paper and cardboard (<1%), and some glass from Western Australia. It is found that SA transports about 14,981 tons of metals (48%), 1,954 tons of plastics (48%) of recovered C&D waste interstate for recycling (GISA, 2019). This is mainly because some parties in the supply chain choose to trade the material to wherever the best economic benefits can be gained.

It is found that VIC transports 32,985 tons of metals (25%), 2,374 tons of paper and cardboard (46%), 2,074 tons of plastics (74%), 445 tons of TLR (45%), 75 tons of glass (7%), and 656 tons of organics (1%) of recovered C&D waste interstate or overseas for reprocessing/recycling (SV, 2017; SV, 2018b), based on an examination of related information from multiple reports (e.g. the *National Waste Report 2018 (Dee, 2018)); Victorian Recycling Industry Annual Report 2016--17 (SV, 2018b); State-wide Waste and Resource Recovery Infrastructure Plan (Victoria 2017) (SV, 2018a)*; and *South Australia's Recycling Activity Survey 2017--18 Report (GISA, 2019)*). The destination of these waste materials originally generated in VIC is most likely SA.

The results also show that QLD transports a minor amount of masonry materials, which is about 243 tons (<0.1%), 64,516 tons of metals (26%), 71 tons of plastics (33%), 53t TLR (<1%) of recovered waste interstate for recycling (QG, 2018); however, the destination of this waste could not be identified due to lack of data. According to the Queensland Government (2018), "organic wastes and masonry materials were recovered in QLD, while most metals, paper and cardboard, and plastics were transported interstate or overseas for further recovery" (QG, 2018).

5.3.2 Transporting C&D waste interstate for landfilling

As C&D waste flows are likely managed by commercial service providers, destinations will change in response to changes in gate fees for reprocessing and landfilling (Dee, 2018). Therefore, some masonry will be transported cross-border to be disposed of in landfill where it has a lower disposal fee or no disposal fee applies. This is more likely the case in eastern regions of Australia, where states or territories share borders, but disposal fees are dramatically different.

It is found that some masonry waste (16,000 tons) originally generated in northern VIC was transported to NSW for landfill in 2016; at the same time, about 68,000 tons of masonry waste from NSW was transported to landfills in northeast VIC (Dee, 2018; SV, 2017). This kind of waste "exchange" also took place between NSW and the ACT. The results show that 561,118 tons of Queanbeyan landfill C&D waste in NSW was sent to the ACT for landfill (QG, 2018); some masonry wastes originally generated in ACT were transported to NSW for landfill due to a shorter transportation distance and no disposal fee applied. Apart from this, according to the *National Waste Report 2018*, NSW also transported about 639,747 tons of masonry waste to QLD for landfill disposal.

5.3.2 Transporting C&D waste overseas for reprocessing/recycling

As some C&D waste materials (such as metals, plastics, and paper and cardboard) are involved in global trade networks, these recovered materials will be transported to wherever there is a market and the best economic benefits can be achieved. According to the "senior manager of a renowned C&D waste recycler 2 in SA", with the same category of materials generated from other sectors (e.g. commercial and industrial waste sector, municipal solid waste sector), some of this generated waste will be transported overseas to China, Malaysia and Indonesia for further processing and recycling.

Based on the study survey, QLD exported about 237,725 tons of metals (75%) and 1,203 tons of plastics (55%) overseas for reprocessing in 2017 (QG, 2018); SA exported about 15, 293 tons of metals (49%) and 1,995 tons of plastics (49%); and WA exported about 2,237 tons of metals (2%), 877 tons of paper and cardboard materials (99%) of recovered C&D waste overseas for reprocessing/recycling in the same year (GISA, 2019). Some of Victoria's waste such as metals, paper and cardboard, plastics, TLR and glass have been transported overseas but the data are combined with interstate waste (SV, 2018b).

5.4 Summary

This chapter described the results of cross-reginal mobility of C&D waste in Australia, including compositions and generation of C&D waste in Australia, fates and flows of C&D waste in Australia, and three main types of C&D waste cross-regional mobility in Australia. By conducting a series of site surveys, expert interviews, expert seminar and desktop surveys (see section 4.3 in Chapter 4), this study offers an in-depth understanding of the treatment and management of C&D waste, particularly the waste cross-regional mobility phenomenon in Australia.

The results show that the recycling rate of masonry materials is relatively high, as masonry materials can be typically produced into recycled aggregates applied in road base/garden base materials. The recycling of masonry materials is very popular in the industry due to the well-established market and competitive price of recycled products. Some combustible materials such as organics, paper and cardboard and TLR made into alternative fuel are increasingly popular in the market, which expands potential treatment methods for these waste materials.

As mentioned, there are three main forms of C&D waste cross-regional mobility in Australia: transport interstate for recycling, transport interstate for landfill, and export overseas for reprocessing/recycling. SA is identified as a centre of C&D waste cross-regional mobility for recycling in Australia. This state receives C&D waste materials for recycling from many other states including the NT, NSW, WA and VIC. Waste cross-regional mobility is quite dynamic in Australia's eastern regions (i.e. NSW, ACT, VIC, and QLD). The findings show that NSW is a major player in transporting its C&D waste, particularly masonry waste to its neighbouring states or territories that share borders but their disposal fees are lower.

In general, although most masonry waste is processed or disposed of within the regions where it was generated, a considerable amount has been transported cross-border for landfill and a minor amount has been sent to other regions for reprocessing/recycling. Waste materials such as metals, plastics, and paper and cardboard are more likely to be reprocessed in other regions, or even overseas.

Chapter 6. Results: Part 2

6.1 Introduction

This chapter illustrates the results for RQ 2 - assessing the benefits and impacts of the cross-regional mobility of C&D waste in Australia based on the methods detailed in section 4.4 in Chapter 4. The results include: environmental impacts of cross-regional mobility of C&D waste in Australia (section 6.2), economic impacts of cross-regional mobility of C&D waste in Australia (section 6.3), and social impacts of cross-regional mobility of C&D waste in Australia (section 6.4). Discussion of the results is presented in section 7.3 in Chapter 7.

6.2 Environmental impacts of cross-regional mobility of C&D waste in Australia

6.2.1 Environmental impacts of scenario 0.0 – base scenario

As presented in section 4.4.6, scenario 0.0 is developed based on the current practice of C&D waste management in Australia and used as the base scenario for scenario analysis (see Figure 6.1). In general, 69.2% of managed waste is recycled intra-regionally, 0.6% of managed waste is recycled cross-regionally, 0.2% of managed waste is energy recovered intra-regionally, non-managed waste is energy recovered cross-regionally, 23.6% of managed waste is landfilled intra-regionally, and 6.4% of managed waste is landfilled cross-regionally. For each waste material, the rates of treatment vary.

Based on the calculation, environmental impacts for 1 t of C&D waste in scenario 0.0 is shown in Figure 6.1 and Table A-6.1 in Appendix B. There are 12 environmental indicators, including GWP 100 years (Global Warming Potential, unit: kg CO2-Equiv.), AP (Acidification Potential, unit, kg SO2-Equiv.), EP (Eutrophication potential, unit: kg Phosphate-Equiv.), ODP (Ozone Layer Depletion Potential, unit: kg R11-Equiv.), ADP elements (Abiotic Depletion elements, unit: kg Sb-Equiv.), ADP fossil (Abiotic Depletion fossil, unit: MJ), FAETP inf. (Freshwater Aquatic Ecotoxicity Pot., unit: kg DCB-Equiv.), HTP inf. (Human Toxicity Potential, unit: kg DCB-Equiv.), MAETP inf. (Marine Aquatic Ecotoxicity Pot., unit: kg DCB-Equiv.), POCP (Photochem, Ozone Creation Potential, unit: kg Etheme-Equiv.), TETP inf. (Terrestic Ecotoxicity Potential, unit: kg DCB-Equiv.) and LO (Land Occupation, unit: m3).

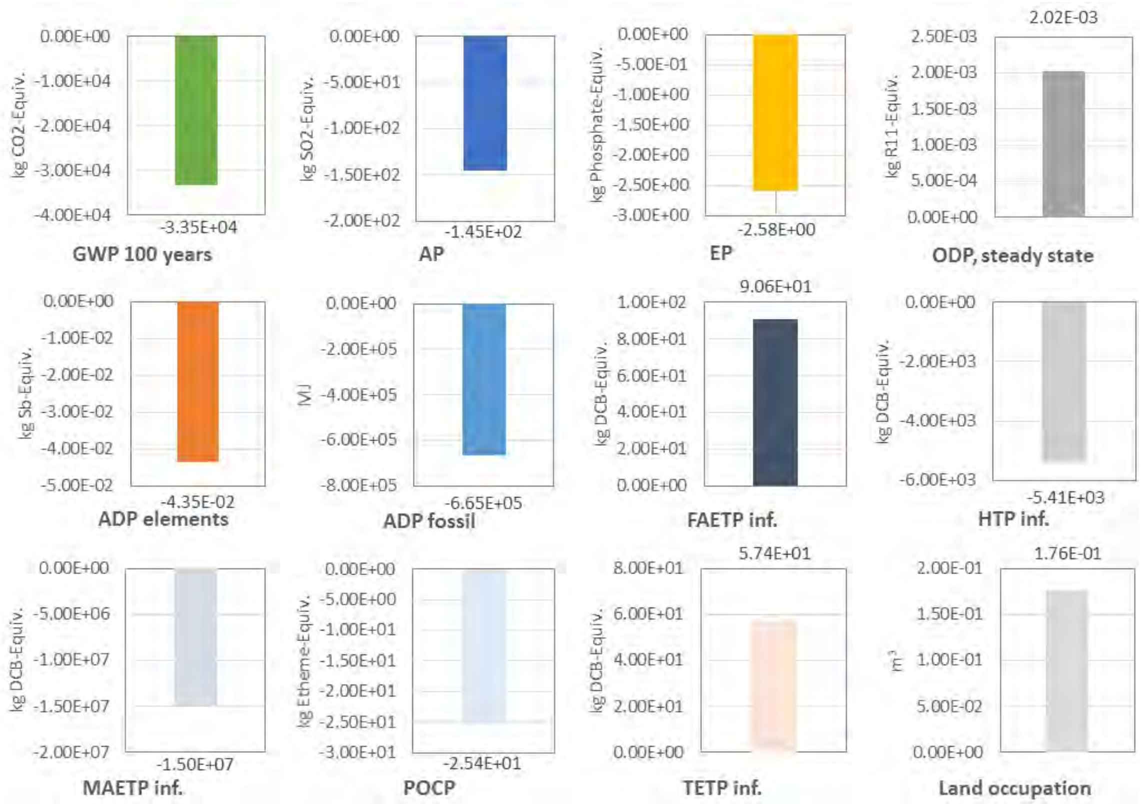


Figure 6.1: Environmental impacts for 1 t of C&D waste (scenario 0.0)

In scenario 0.0, considering the life cycle stages of C&D waste including waste collection and onsite sorting, transportation, waste pre-processing, recycling, energy recovery and landfilling, environmental impacts for 1 t of C&D waste are mainly negative value. This is because in scenario 0.0 recycling rates of critical waste materials such as masonry waste and metals are relatively high. The recycling rate of masonry waste and metals are 69.2% and 92.1% respectively. As discussed before, the recycling of waste can reduce life cycle environmental impacts. As a result, environmental impacts of treating 1 t of C&D waste are shown including GWP 100 years (-3.35E+04 kg CO2-Equiv.), AP (-1.45E+02 kg SO2-Equiv.), EP (-2.58E+00 kg Phosphate-Equiv.), ODP (2.02E+03 kg R11-Equiv.), ADP elements (-4.35E-02 kg Sb-Equiv.), ADP fossil (-6.65E+05 MJ), FAETP inf. (9.06E+01 kg DCB-Equiv.), HTP inf. (-5.41E+03 kg DCB-Equiv.), MAETP inf. (-1.50E+07 kg DCB-Equiv.), POCP (-2.54EE+01 kg Etheme-Equiv.), TETP inf. (5.74E+01 kg DCB-Equiv.) and Land occupation (1.76E-01m^3). Causes for these results will be discussed in more detail in Chapter 7.

To be specific, environmental impacts for each life cycle stage for 1 t of C&D waste are also calculated and will be detailed as follows.

For GWP 100 years, environmental impact waste collection and onsite sorting values include 1.18E-01 kg CO2-Equiv.; transportation values 1.78E-01 kg CO2-Equiv.; waste pre-processing values 2.69E+00 kg CO2-Equiv.; recycling values -7.17E+05 kg CO2-Equiv.; energy recovery values -9.99E+02 kg CO2-Equiv.; landfilling values 3.93E+04 kg CO2-Equiv.; and total values -3.35E+04 kg CO2-Equiv. (Figure 6.2).

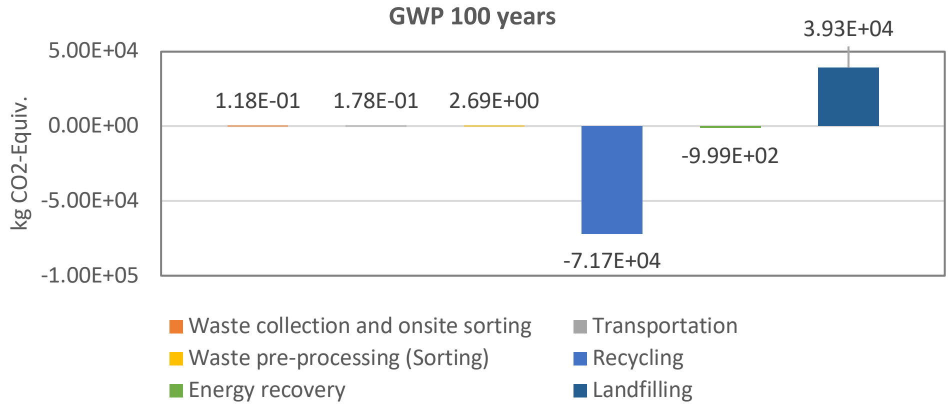


Figure 6.2: Environmental impacts for each life cycle stage for 1 t of C&D waste (GWP 100 years)

For AP, environmental impact waste collection and onsite sorting values include 1.10E-03 kg SO2-Equiv.; transportation values 1.68E-03 kg SO2-Equiv.; waste pre-processing values 1.81E-02 kg SO2-Equiv.; recycling values -1.84E+02 kg SO2-Equiv., energy recovery values -2.70E+00 kg SO2-Equiv.; landfilling values 4.34E+01 kg SO2-Equiv.; and total values -1.45E+02 kg SO2-Equiv. (Figure 6.3).

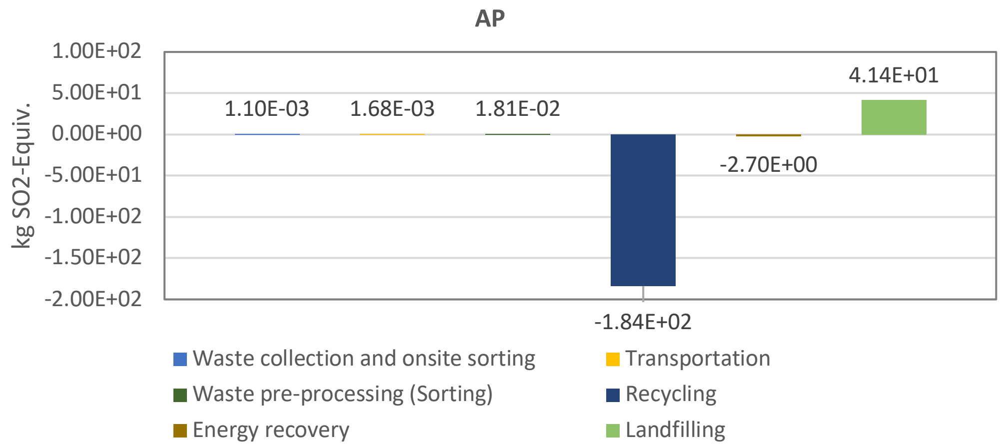


Figure 6.3: Environmental impacts for each life cycle stage for 1 t of C&D waste (AP)

For EP, environmental impact waste collection and onsite sorting values include 9.64E-05 kg Phosphate-Equiv.; transportation values 1.82E-04 kg Phosphate-Equiv.; waste pre-processing values 4.43E-03 kg Phosphate-Equiv.; recycling values -7.35E+00 kg Phosphate-Equiv.; energy recovery values -5.39E-01 kg Phosphate-Equiv.; landfilling values 5.31E+00 kg Phosphate-Equiv.; and total values -2.58E+00 kg Phosphate-Equiv. (Figure 4.4).

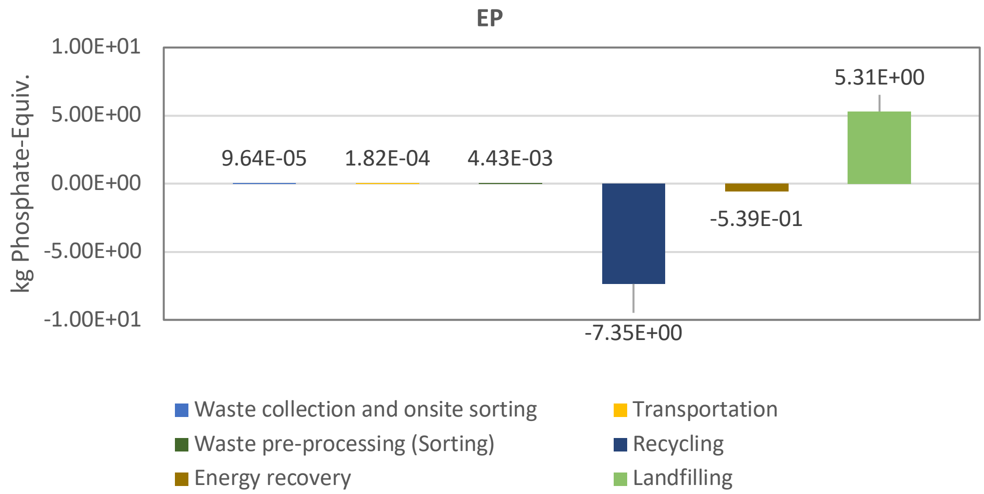


Figure 6.4: Environmental impacts for each life cycle stage for 1 t of C&D waste (EP)

For ODP, environmental impact waste collection and onsite sorting values include 5.78E-16 kg R11-Equiv.; transportation values 2.75E-15 kg R11-Equiv.; waste pre-processing values 6.08E-13 kg R11-Equiv.; recycling values 2.21E-03 kg R11-Equiv., energy recovery values -6.81E-09 kg R11-Equiv.; landfilling values -1.89 E-04 kg R11-Equiv.; and total values 2.02E-03 kg R11-Equiv. (Figure 6.5).

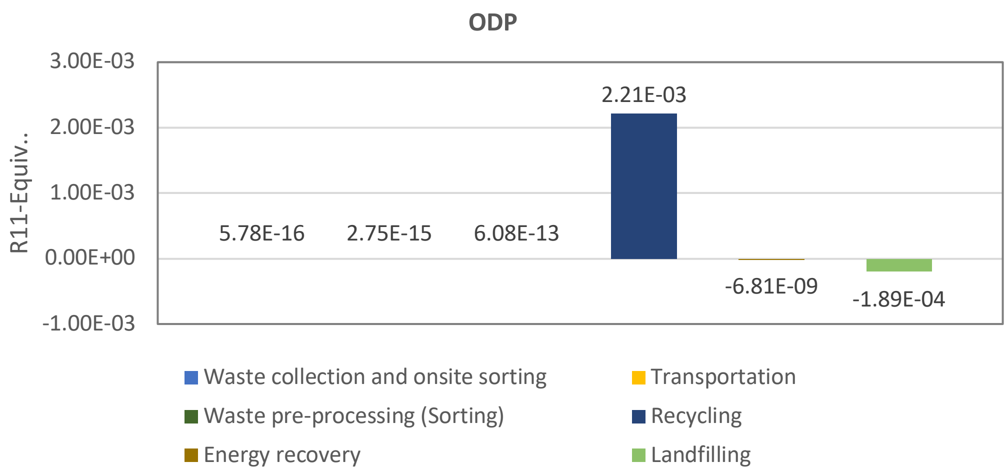


Figure 6.5: Environmental impacts for each life cycle stage for 1 t of C&D waste (ODP)

For ADP elements, environmental impact waste collection and onsite sorting values include 3.40E-08 kg Sb-Equiv.; transportation values 9.48E-08 kg Sb-Equiv.; waste pre-processing values 3.59E-06 kg Sb-Equiv.; recycling values -4.83E-02 kg Sb-Equiv.; energy recovery values -2.11E-03 kg Sb-Equiv.; landfilling values 4.77E-03 kg Sb-Equiv.; and total values -4.35E-02 kg Sb-Equiv. (Figure 6.6).

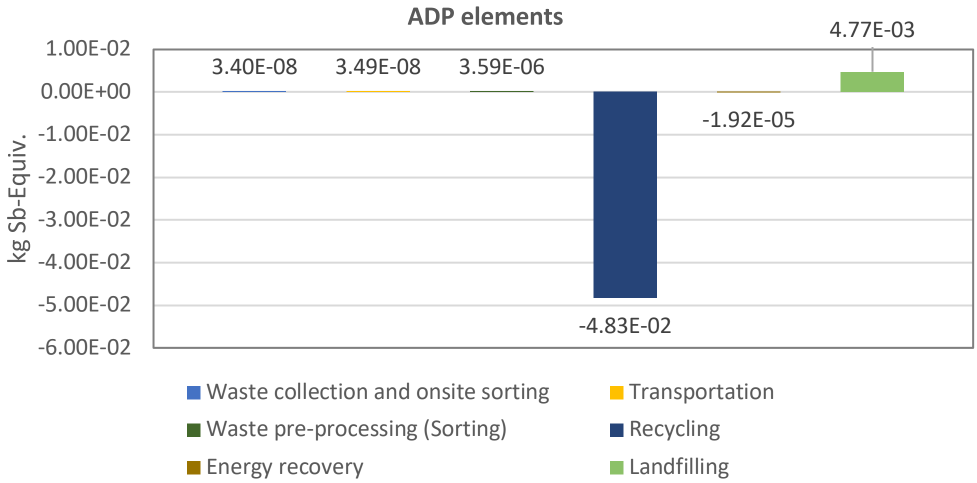


Figure 6.6: Environmental impacts for each life cycle stage for 1 t of C&D waste (ADP elements)

For ADP fossil, environmental impact waste collection and onsite sorting values include 2.87E+01 MJ; transportation values 8.60E+01 MJ; waste pre-processing values 5.06E+01 MJ; recycling values -7.67E+05 MJ; energy recovery values -4.51E+04 MJ; landfilling values 1.03E+05 MJ; and total values -6.65E+05 MJ. (Figure 6.7)

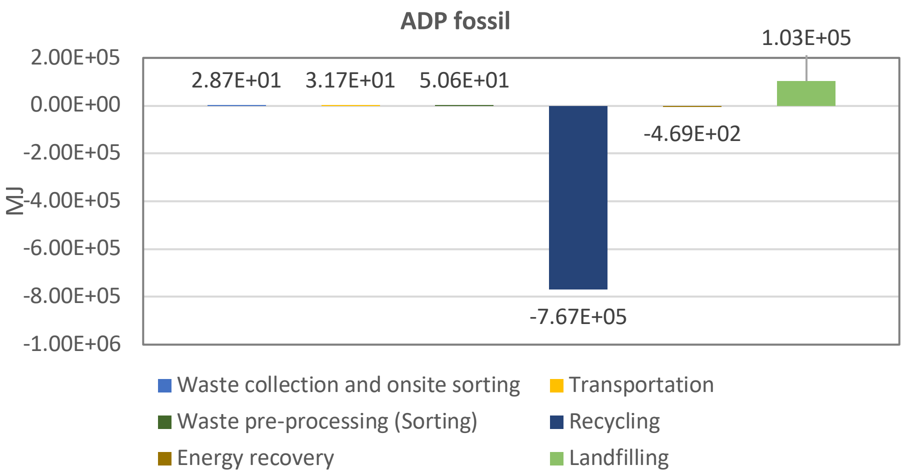


Figure 6.7: Environmental impacts for each life cycle stage for 1 t of C&D waste (ADP fossil)

For FAETP inf., environmental impact waste collection and onsite sorting values include 4.08E-03 kg DCB-Equiv.; transportation values 1.47E-02 kg DCB-Equiv.; waste pre-processing values 2.03E-02 kg DCB-Equiv.; recycling values 7.64E+01 kg DCB-Equiv.; energy recovery values -1.42E+01 kg DCB-Equiv.; landfilling values 1.43E+01 kg DCB-Equiv.; and total values 9.06E+01 kg DCB-Equiv. (Figure 6.8).

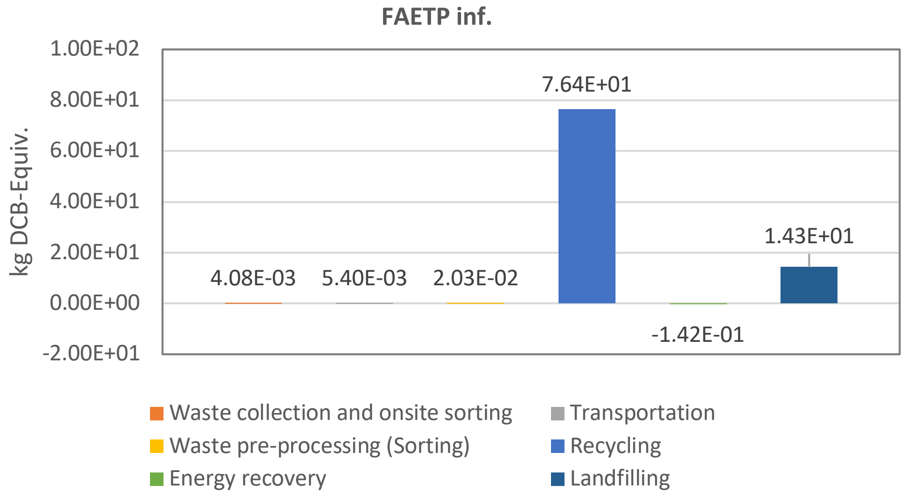


Figure 6.8: Environmental impacts for each life cycle stage for 1 t of C&D waste (FAETP inf.)

For HTP inf., environmental impact waste collection and onsite sorting values include 2.50E-02 kg DCB-Equiv.; transportation values 8.80E-02 kg DCB-Equiv.; waste pre-processing values 2.35E-01 kg DCB-Equiv.; recycling values -6.60E+03 kg DCB-Equiv.; energy recovery values -9.12E+00 kg DCB-Equiv.; landfilling values 1.20E+03 kg DCB-Equiv.; and total values -5.41E+03 kg DCB-Equiv. (Figure 6.9).

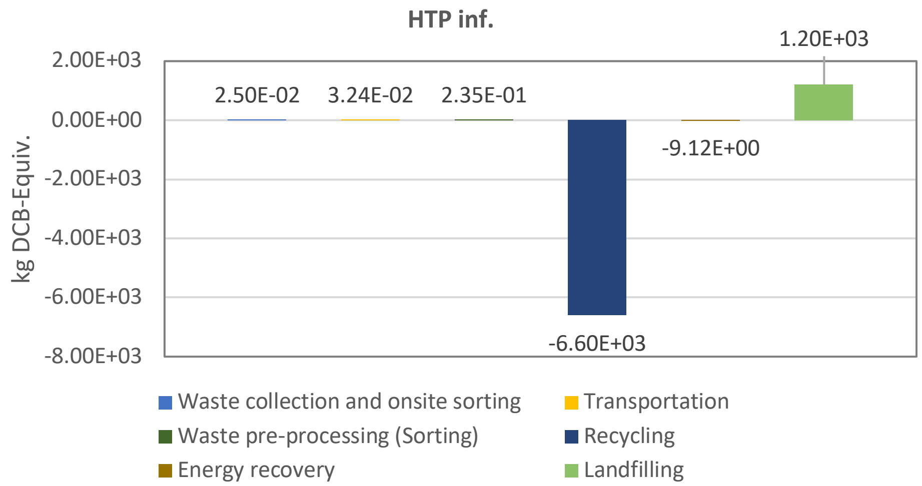


Figure 6.9: Environmental impacts for each life cycle stage for 1 t of C&D waste (HTP inf.)

For MAETP inf., environmental impact waste collection and onsite sorting values include 1.64E+01 kg DCB-Equiv.; transportation values 5.85E+01 kg DCB-Equiv.; waste pre-processing values 1.09E+02 kg DCB-Equiv.; recycling values -1.64E+07 kg DCB-Equiv.; energy recovery values -3.74E+02 kg DCB-Equiv.; landfilling values 1.40E+06 kg DCB-Equiv.; and total values -1.50E+07 kg DCB-Equiv. (Figure 6.10).

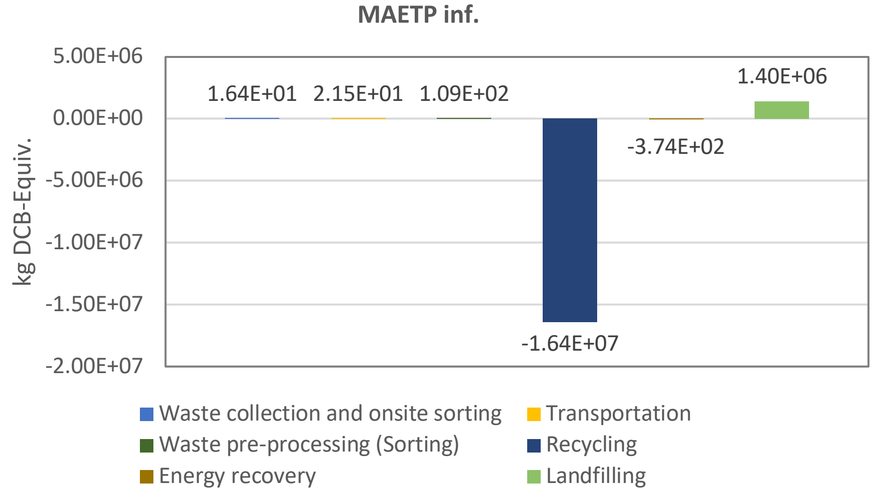


Figure 6.10: Environmental impacts for each life cycle stage for 1 t of C&D waste (MAETP inf.)

For POCP, environmental impact waste collection and onsite sorting values include 1.61E-04 kg Etheme-Equiv.; transportation values 5.02E-04 kg Etheme-Equiv.; waste pre-processing values 5.02E-04 kg Etheme-Equiv.; recycling values -3.80E+01 kg Etheme-Equiv.; energy recovery values -2.78E+01 kg Etheme-Equiv.; landfilling values -1.29E+01 kg Etheme-Equiv.; and total values -2.54E+01 kg Etheme-Equiv. (Figure 6.11).

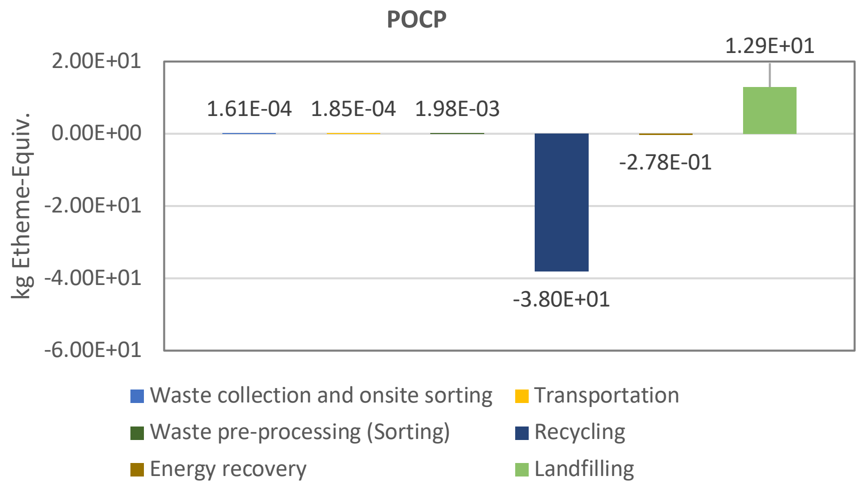


Figure 6.11: Environmental impacts for each life cycle stage for 1 t of C&D waste (POCP)

For TETP inf., environmental impact waste collection and onsite sorting values include 1.66E-04 kg DCB-Equiv.; transportation values 7.01E-04 kg DCB-Equiv.; waste pre-processing values 4.99E-03 kg DCB-Equiv.; recycling values 2.12E+01 kg DCB-Equiv.; energy recovery values -1.01E-01 kg DCB-Equiv.; landfilling values 3.62E+01 kg DCB-Equiv.; and total values 5.74E+01 kg DCB-Equiv. (Figure 6.12).

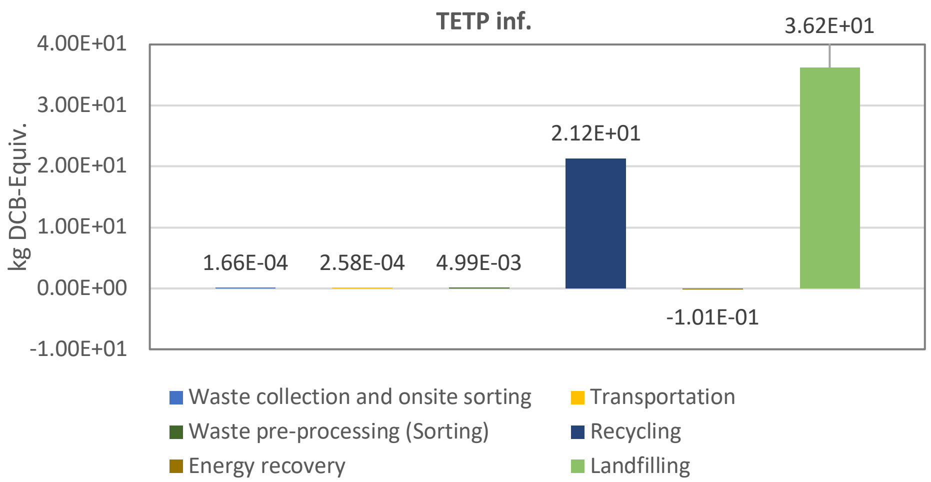


Figure 6.12: Environmental impacts for each life cycle stage for 1 t of C&D waste (TETP inf.)

For Land occupation, environmental impact recycling values include 2.26E-02 m3, energy recovery values 4.75E-03 m3; landfilling values 4.52E-01 m3; and total values 4.79E-01 m3. (Figure 6.13).

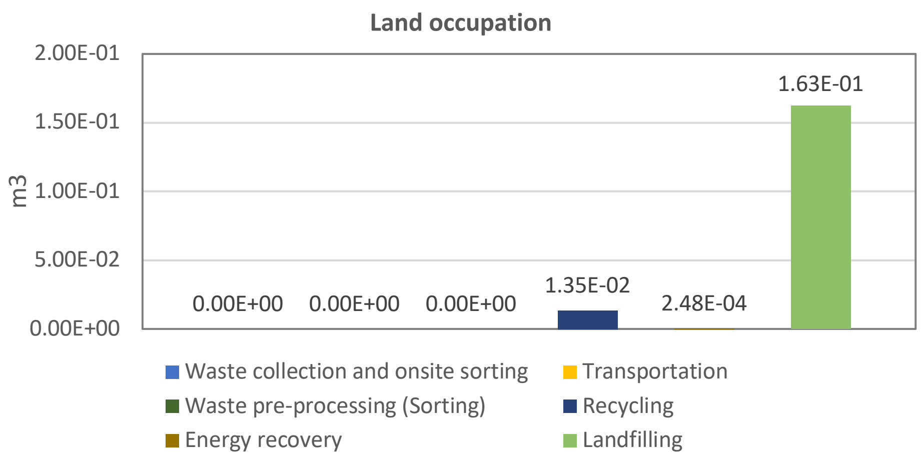


Figure 6.13: Environmental impacts for each life cycle stage for 1 t of C&D waste (Land occupation

For base scenario, Australia produced about 20.4 million C&D waste. Based on the calculation, the environmental impacts for generated C&D waste in the current situation are shown in Figure 6.14 with results including GWP 100 years (-6.73E+11 kg CO2-Equiv.), AP (-2.92E+09 kg SO2-Equiv.), EP (-5.18E+07 kg Phosphate-Equiv.), ODP (4.06E+04 kg R11-Equiv.), ADP elements (-8.75E+05 kg Sb-Equiv.), ADP fossil (-1.34E+13 MJ), FAETP inf. (1.82E+09 kg DCB-Equiv.), HTP inf. (-1.09E+11 kg DCB-Equiv.), MAETP inf. (-3.01E+14 kg DCB-Equiv.), POCP (-5.10E+08 kg Etheme-Equiv.), TETP inf. (1.15E+09 kg DCB-Equiv.) andand Land occupation (3.55E+06 m3). Detailed results are shown in Table A-6.2 in Appendix B.

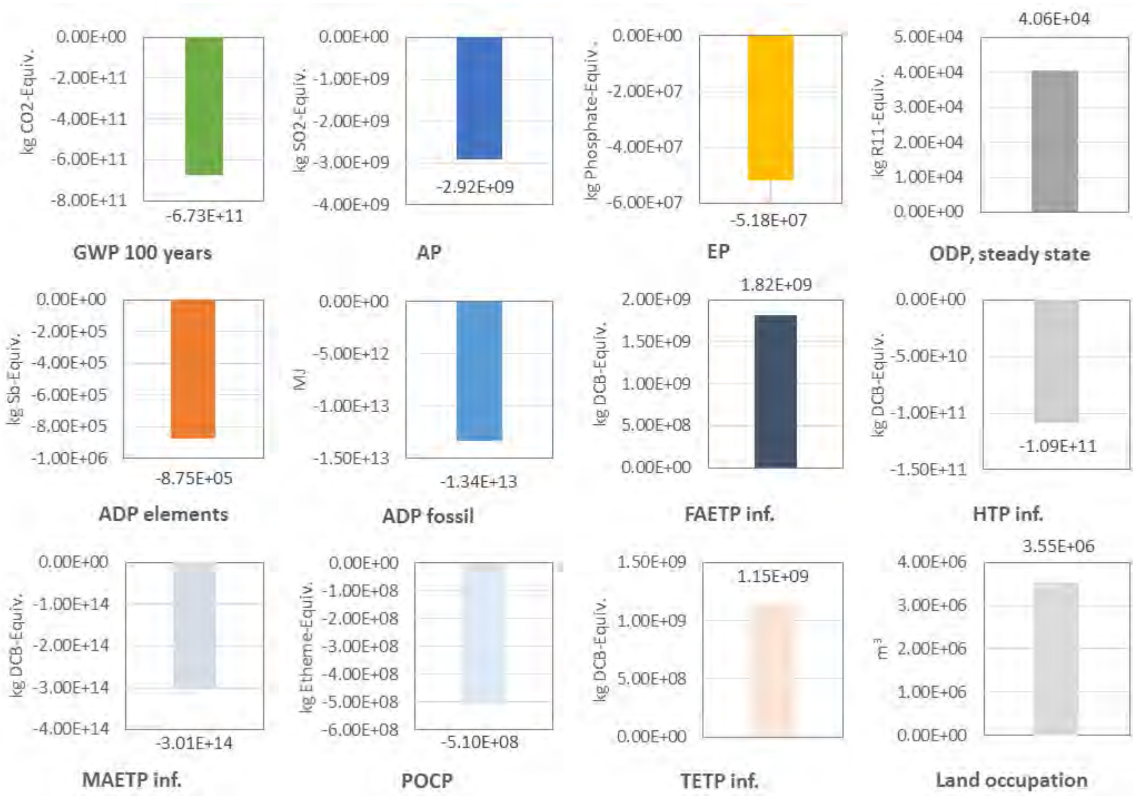


Figure 6.14: Environmental impacts for generated C&D waste currently in Australia

6.2.2 Environmental impacts of scenario I

According to the scenario setting in section 4.4.6 (Chapter 4 Methodology), scenario setting I for treatment and disposal options will not consider energy recovery, but instead consider recycling and landfilling (cross-regional mobility + , recycling rate +, No energy recovery). In scenario setting I, there are 25 scenarios from scenario 1.1 to scenario 1.25, developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, the recycling rate will be increased every 25% from 0% to 95% while the landfilling rate will be decreased from 100% to 5% accordingly. The percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%. Scenario setting I percentages are shown in Figure 6.15.

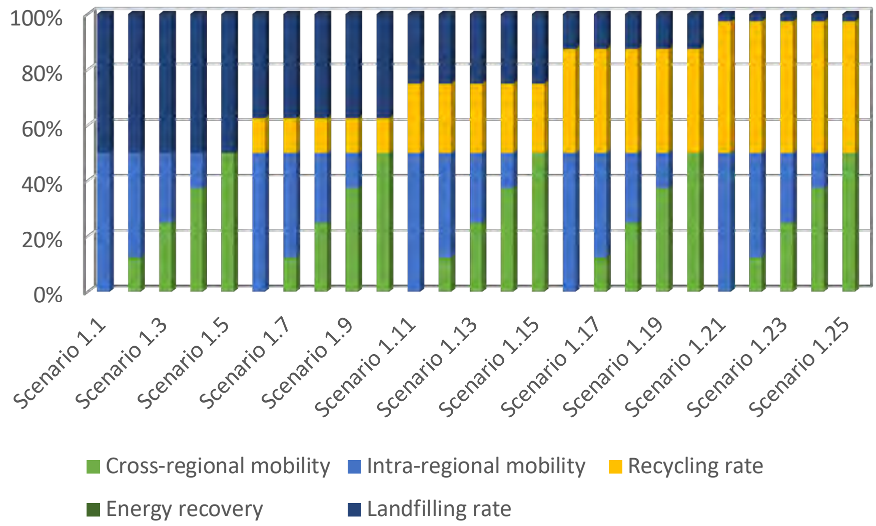


Figure 6.15: Scenario setting I

Based on the data, environmental impacts for generated C&D waste in Australia in scenario setting I are calculated. For scenario 1.1, the results show GWP 100 years (3.07E+12 kg CO2-Equiv.), AP (5.29E+09 kg SO2-Equiv.), EP (3.27E+08 kg Phosphate-Equiv.), ODP (-5.20E+04 kg R11-Equiv.), ADP elements (1.39E+06 kg Sb-Equiv.), ADP fossil (2.02E+13 MJ), FAETP inf. (-8.83E+08 kg DCB-Equiv.), HTP inf. (2.18E+11 kg DCB-Equiv.), MAETP inf. (4.94E+14 kg DCB-Equiv.), POCP (1.24E+09 kg Etheme-Equiv.), TETP inf. (8.77E+08 kg DCB-Equiv.) and Land occupation (9.09 E+06 m^3). The detailed results for each scenario are shown in Table 6.1.

Table 6.1(a): Environmental impacts of scenario I

No.	Indicators	Unit	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5
EI1	GWP 100 years	kg CO2-Equiv.	3.07E+12	3.07E+12	3.07E+12	3.07E+12	3.07E+12
EI2	AP	kg SO2-Equiv.	5.29E+09	5.29E+09	5.29E+09	5.29E+09	5.29E+09
EI3	EP	kg Phosphate-Equiv.	3.27E+08	3.27E+08	3.27E+08	3.27E+08	3.27E+08
EI4	ODP, steady state	kg R11-Equiv.	-5.20E+04	-5.20E+04	-5.20E+04	-5.20E+04	-5.20E+04
EI5	ADP elements	kg Sb-Equiv.	1.39E+06	1.39E+06	1.39E+06	1.39E+06	1.39E+06
EI6	ADP fossil	MJ	2.02E+13	2.02E+13	2.02E+13	2.02E+13	2.02E+13
EI7	FAETP inf.	kg DCB-Equiv.	-8.83E+08	-8.83E+08	-8.83E+08	-8.83E+08	-8.83E+08
EI8	HTP inf.	kg DCB-Equiv.	2.18E+11	2.18E+11	2.18E+11	2.18E+11	2.18E+11
EI9	MAETP inf.	kg DCB-Equiv.	4.94E+14	4.94E+14	4.94E+14	4.94E+14	4.94E+14
EI10	POCP	kg Etheme-Equiv.	1.24E+09	1.24E+09	1.24E+09	1.24E+09	1.24E+09
EI11	TETP inf.	kg DCB-Equiv.	8.77E+08	8.77E+08	8.77E+08	8.77E+08	8.77E+08
E12	Land occupation	m^3	9.09E+06	9.09E+06	9.09E+06	9.09E+06	9.09E+06

Table 6.1 (b): Environmental impacts of scenario I (cont'd)

No.	Indicators	Unit	Scenario 1.6	Scenario 1.7	Scenario 1.8	Scenario 1.9	Scenario 1.10
EI1	GWP 100 years	kg CO2-Equiv.	1.49E+12	1.49E+12	1.49E+12	1.49E+12	1.49E+12
EI2	AP	kg SO2-Equiv.	1.68E+09	1.68E+09	1.68E+09	1.68E+09	1.68E+09
EI3	EP	kg Phosphate-Equiv.	1.18E+08	1.18E+08	1.18E+08	1.18E+08	1.18E+08
EI4	ODP, steady state	kg R11-Equiv.	-1.80E+04	-1.80E+04	-1.80E+04	-1.80E+04	-1.80E+04
EI5	ADP elements	kg Sb-Equiv.	1.51E+04	1.51E+04	1.51E+04	1.51E+04	1.51E+04
EI6	ADP fossil	MJ	6.01E+12	6.01E+12	6.01E+12	6.01E+12	6.01E+12
EI7	FAETP inf.	kg DCB-Equiv.	-6.96E+08	-6.96E+08	-6.96E+08	-6.95E+08	-6.95E+08
EI8	HTP inf.	kg DCB-Equiv.	-4.21E+09	-4.21E+09	-4.21E+09	-4.21E+09	-4.21E+09
EI9	MAETP inf.	kg DCB-Equiv.	-2.94E+13	-2.94E+13	-2.94E+13	-2.94E+13	-2.94E+13

EI10	POCP	kg Etheme-Equiv.	5.33E+08	5.33E+08	5.33E+08	5.33E+08	5.33E+08
EI11	TETP inf.	kg DCB-Equiv.	4.76E+08	4.76E+08	4.76E+08	4.76E+08	4.76E+08
E12	Land occupation	m^3	6.93E+06	6.93E+06	6.93E+06	6.93E+06	6.93E+06

Table 6.1(c): Environmental impacts of scenario I (cont'd)

No.	Indicators	Unit	Scenario 1.11	Scenario 1.12	Scenario 1.13	Scenario 1.14	Scenario 1.15
EI1	GWP 100 years	kg CO2-Equiv.	-9.02E+10	-9.02E+10	-9.02E+10	-9.02E+10	-9.02E+10
EI2	AP	kg SO2-Equiv.	-1.93E+09	-1.93E+09	-1.93E+09	-1.93E+09	-1.93E+09
EI3	EP	kg Phosphate-Equiv.	-9.08E+07	-9.08E+07	-9.08E+07	-9.07E+07	-9.07E+07
EI4	ODP, steady state	kg R11-Equiv.	1.59E+04	1.59E+04	1.59E+04	1.59E+04	1.59E+04
EI5	ADP elements	kg Sb-Equiv.	-1.36E+06	-1.36E+06	-1.36E+06	-1.36E+06	-1.36E+06
EI6	ADP fossil	MJ	-8.17E+12	-8.17E+12	-8.17E+12	-8.17E+12	-8.17E+12
EI7	FAETP inf.	kg DCB-Equiv.	-5.08E+08	-5.08E+08	-5.08E+08	-5.08E+08	-5.08E+08
EI8	HTP inf.	kg DCB-Equiv.	-2.26E+11	-2.26E+11	-2.26E+11	-2.26E+11	-2.26E+11
EI9	MAETP inf.	kg DCB-Equiv.	-5.53E+14	-5.53E+14	-5.53E+14	-5.53E+14	-5.53E+14
EI10	POCP	kg Etheme-Equiv.	-1.79E+08	-1.79E+08	-1.79E+08	-1.79E+08	-1.79E+08
EI11	TETP inf.	kg DCB-Equiv.	7.43E+07	7.43E+07	7.43E+07	7.43E+07	7.43E+07
E12	Land occupation	m^3	4.77E+06	4.77E+06	4.77E+06	4.77E+06	4.77E+06

Table 6.1(d): Environmental impacts of scenario I (cont'd)

No.	Indicators	Unit	Scenario 1.16	Scenario 1.17	Scenario 1.18	Scenario 1.19	Scenario 1.20
EI1	GWP 100 years	kg CO2-Equiv.	-1.67E+12	-1.67E+12	-1.67E+12	-1.67E+12	-1.67E+12
EI2	AP	kg SO2-Equiv.	-5.54E+09	-5.54E+09	-5.54E+09	-5.54E+09	-5.54E+09
EI3	EP	kg Phosphate-Equiv.	-3.00E+08	-3.00E+08	-3.00E+08	-3.00E+08	-3.00E+08
EI4	ODP, steady state	kg R11-Equiv.	4.99E+04	4.99E+04	4.99E+04	4.99E+04	4.99E+04
EI5	ADP elements	kg Sb-Equiv.	-2.74E+06	-2.74E+06	-2.74E+06	-2.74E+06	-2.74E+06

EI6	ADP fossil	MJ	-2.23E+13	-2.23E+13	-2.23E+13	-2.23E+13	-2.23E+13
EI7	FAETP inf.	kg DCB-Equiv.	-3.21E+08	-3.21E+08	-3.21E+08	-3.21E+08	-3.21E+08
EI8	HTP inf.	kg DCB-Equiv.	-4.48E+11	-4.48E+11	-4.48E+11	-4.48E+11	-4.48E+11
EI9	MAETP inf.	kg DCB-Equiv.	-1.08E+15	-1.08E+15	-1.08E+15	-1.08E+15	-1.08E+15
EI10	POCP	kg Etheme-Equiv.	-8.90E+08	-8.90E+08	-8.90E+08	-8.90E+08	-8.90E+08
EI11	TETP inf.	kg DCB-Equiv.	-3.27E+08	-3.27E+08	-3.27E+08	-3.27E+08	-3.27E+08
E12	Land occupation	m^3	2.61E+06	2.61E+06	2.61E+06	2.61E+06	2.61E+06

Table 6.1(e): The Environmental impacts of scenario I (cont'd)

No.	Indicators	Unit	Scenario 1.21	Scenario 1.22	Scenario 1.23	Scenario 1.24	Scenario 1.25
EI1	GWP 100 years	kg CO2-Equiv.	-2.93E+12	-2.93E+12	-2.93E+12	-2.93E+12	-2.93E+12
EI2	AP	kg SO2-Equiv.	-8.43E+09	-8.43E+09	-8.43E+09	-8.43E+09	-8.43E+09
EI3	EP	kg Phosphate-Equiv.	-4.67E+08	-4.67E+08	-4.67E+08	-4.67E+08	-4.67E+08
EI4	ODP, steady state	kg R11-Equiv.	7.70E+04	7.70E+04	7.70E+04	7.70E+04	7.70E+04
EI5	ADP elements	kg Sb-Equiv.	-3.85E+06	-3.85E+06	-3.85E+06	-3.85E+06	-3.85E+06
EI6	ADP fossil	MJ	-3.37E+13	-3.37E+13	-3.37E+13	-3.37E+13	-3.37E+13
EI7	FAETP inf.	kg DCB-Equiv.	-1.71E+08	-1.71E+08	-1.71E+08	-1.71E+08	-1.71E+08
EI8	HTP inf.	kg DCB-Equiv.	-6.26E+11	-6.26E+11	-6.26E+11	-6.26E+11	-6.26E+11
EI9	MAETP inf.	kg DCB-Equiv.	-1.49E+15	-1.49E+15	-1.49E+15	-1.49E+15	-1.49E+15
EI10	POCP	kg Etheme-Equiv.	-1.46E+09	-1.46E+09	-1.46E+09	-1.46E+09	-1.46E+09
EI11	TETP inf.	kg DCB-Equiv.	-6.48E+08	-6.48E+08	-6.48E+08	-6.48E+08	-6.48E+08
E12	Land occupation	m^3	8.86E+05	8.86E+05	8.86E+05	8.86E+05	8.86E+05

6.2.3 Environmental impacts of scenario II

Scenario setting II for treatment and disposal options will not consider energy recovery, but will consider recycling and landfilling (cross-regional mobility +, landfilling rate +, recycling rate -, No energy recovery). In scenario setting II, there are 25 scenarios from scenario 2.1 to scenario 2.25, developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, the recycling rate will be decreased every 25% from 95% to 0% while the landfilling rate will be increased from 5% to 100% accordingly. The percentage of cross-regional mobility of the waste will be allocated from 0% to 100% by every 25%. Scenario setting II details are shown in Figure 6.16.

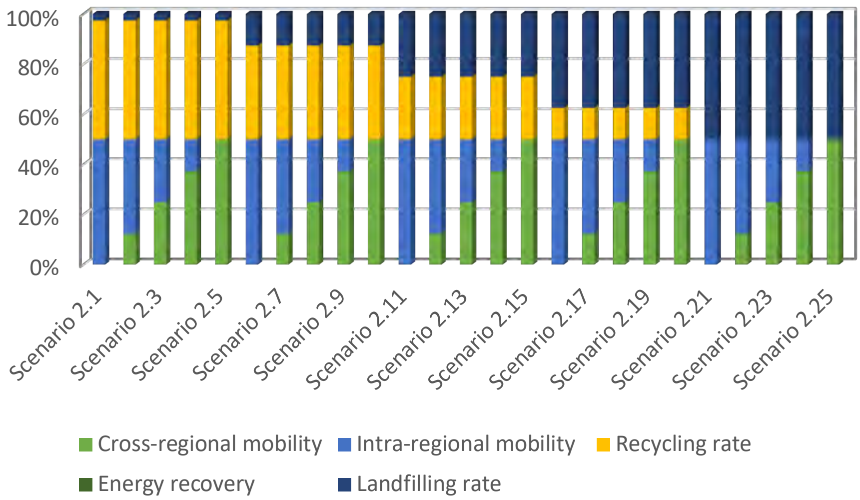


Figure 6.16: Scenario setting II

Based on the data, environmental impacts for generated C&D waste in Australia in scenario setting II are calculated. For scenario 2.1, the results show GWP 100 years (-2.93E+12 kg CO2-Equiv.), AP (-8.43E+09 kg SO2-Equiv.), EP (-4.67E+08 kg Phosphate-Equiv.), ODP (7.70E+04 kg R11-Equiv.), ADP elements (-3.85E+06 kg Sb-Equiv.), ADP fossil (-3.37E+13 MJ), FAETP inf. (-1.71E+08 kg DCB-Equiv.), HTP inf. (-6.26E+11 kg DCB-Equiv.), MAETP inf. (-1.49E+15 kg DCB-Equiv.), POCP (-1.46E+09 kg Etheme-Equiv.), TETP inf. (-6.48E+08 kg DCB-Equiv.) and Land occupation (8.86E+05 E+06 m^3). The detailed results for each scenario are shown in Table 6.2.

Table 6.2(a): Environmental impacts of scenario II

No.	Indicators	Unit	Scenario 2.1	Scenario 2.2	Scenario 2.3	Scenario 2.4	Scenario 2.5
EI1	GWP 100 years	kg CO2-Equiv.	-2.93E+12	-2.93E+12	-2.93E+12	-2.93E+12	-2.93E+12
EI2	AP	kg SO2-Equiv.	-8.43E+09	-8.43E+09	-8.43E+09	-8.43E+09	-8.43E+09
EI3	EP	kg Phosphate-Equiv.	-4.67E+08	-4.67E+08	-4.67E+08	-4.67E+08	-4.67E+08
EI4	ODP, steady state	kg R11-Equiv.	7.70E+04	7.70E+04	7.70E+04	7.70E+04	7.70E+04
EI5	ADP elements	kg Sb-Equiv.	-3.85E+06	-3.85E+06	-3.85E+06	-3.85E+06	-3.85E+06
EI6	ADP fossil	MJ	-3.37E+13	-3.37E+13	-3.37E+13	-3.37E+13	-3.37E+13
EI7	FAETP inf.	kg DCB-Equiv.	-1.71E+08	-1.71E+08	-1.71E+08	-1.71E+08	-1.71E+08
EI8	HTP inf.	kg DCB-Equiv.	-6.26E+11	-6.26E+11	-6.26E+11	-6.26E+11	-6.26E+11
EI9	MAETP inf.	kg DCB-Equiv.	-1.49E+15	-1.49E+15	-1.49E+15	-1.49E+15	-1.49E+15
EI10	POCP	kg Etheme-Equiv.	-1.46E+09	-1.46E+09	-1.46E+09	-1.46E+09	-1.46E+09
EI11	TETP inf.	kg DCB-Equiv.	-6.48E+08	-6.48E+08	-6.48E+08	-6.48E+08	-6.48E+08
E12	Land occupation	m^3	8.86E+05	8.86E+05	8.86E+05	8.86E+05	8.86E+05

Table 6.2(b): Environmental impacts of scenario II (cont'd)

No.	Indicators	Unit	Scenario 2.6	Scenario 2.7	Scenario 2.8	Scenario 2.9	Scenario 2.10
EI1	GWP 100 years	kg CO2-Equiv.	-1.67E+12	-1.67E+12	-1.67E+12	-1.67E+12	-1.67E+12
EI2	AP	kg SO2-Equiv.	-5.54E+09	-5.54E+09	-5.54E+09	-5.54E+09	-5.54E+09
EI3	EP	kg Phosphate-Equiv.	-3.00E+08	-3.00E+08	-3.00E+08	-3.00E+08	-3.00E+08
EI4	ODP, steady state	kg R11-Equiv.	4.99E+04	4.99E+04	4.99E+04	4.99E+04	4.99E+04
EI5	ADP elements	kg Sb-Equiv.	-2.74E+06	-2.74E+06	-2.74E+06	-2.74E+06	-2.74E+06
EI6	ADP fossil	MJ	-2.23E+13	-2.23E+13	-2.23E+13	-2.23E+13	-2.23E+13
EI7	FAETP inf.	kg DCB-Equiv.	-3.21E+08	-3.21E+08	-3.21E+08	-3.21E+08	-3.21E+08
EI8	HTP inf.	kg DCB-Equiv.	-4.48E+11	-4.48E+11	-4.48E+11	-4.48E+11	-4.48E+11
EI9	MAETP inf.	kg DCB-Equiv.	-1.08E+15	-1.08E+15	-1.08E+15	-1.08E+15	-1.08E+15

EI10	POCP	kg Etheme-Equiv.	-8.90E+08	-8.90E+08	-8.90E+08	-8.90E+08	-8.90E+08
EI11	TETP inf.	kg DCB-Equiv.	-3.27E+08	-3.27E+08	-3.27E+08	-3.27E+08	-3.27E+08
E12	Land occupation	m^3	2.61E+06	2.61E+06	2.61E+06	2.61E+06	2.61E+06

Table 6.2(c): Environmental impacts of scenario II (cont'd)

No.	Indicators	Unit	Scenario 2.11	Scenario 2.12	Scenario 2.13	Scenario 2.14	Scenario 2.15
EI1	GWP 100 years	kg CO2-Equiv.	-9.02E+10	-9.02E+10	-9.02E+10	-9.02E+10	-9.02E+10
EI2	AP	kg SO2-Equiv.	-1.93E+09	-1.93E+09	-1.93E+09	-1.93E+09	-1.93E+09
EI3	EP	kg Phosphate-Equiv.	-9.08E+07	-9.08E+07	-9.08E+07	-9.07E+07	-9.07E+07
EI4	ODP, steady state	kg R11-Equiv.	1.59E+04	1.59E+04	1.59E+04	1.59E+04	1.59E+04
EI5	ADP elements	kg Sb-Equiv.	-1.36E+06	-1.36E+06	-1.36E+06	-1.36E+06	-1.36E+06
EI6	ADP fossil	MJ	-8.17E+12	-8.17E+12	-8.17E+12	-8.17E+12	-8.17E+12
EI7	FAETP inf.	kg DCB-Equiv.	-5.08E+08	-5.08E+08	-5.08E+08	-5.08E+08	-5.08E+08
EI8	HTP inf.	kg DCB-Equiv.	-2.26E+11	-2.26E+11	-2.26E+11	-2.26E+11	-2.26E+11
EI9	MAETP inf.	kg DCB-Equiv.	-5.53E+14	-5.53E+14	-5.53E+14	-5.53E+14	-5.53E+14
EI10	POCP	kg Etheme-Equiv.	-1.79E+08	-1.79E+08	-1.79E+08	-1.79E+08	-1.79E+08
EI11	TETP inf.	kg DCB-Equiv.	7.43E+07	7.43E+07	7.43E+07	7.43E+07	7.43E+07
E12	Land occupation	m^3	4.77E+06	4.77E+06	4.77E+06	4.77E+06	4.77E+06

Table 6.2(d): Environmental impacts of scenario II (cont'd)

No.	Indicators	Unit	Scenario 2.16	Scenario 2.17	Scenario 2.18	Scenario 2.19	Scenario 2.20
EI1	GWP 100 years	kg CO2-Equiv.	1.49E+12	1.49E+12	1.49E+12	1.49E+12	1.49E+12
EI2	AP	kg SO2-Equiv.	1.68E+09	1.68E+09	1.68E+09	1.68E+09	1.68E+09
EI3	EP	kg Phosphate-Equiv.	1.18E+08	1.18E+08	1.18E+08	1.18E+08	1.18E+08
EI4	ODP, steady state	kg R11-Equiv.	-1.80E+04	-1.80E+04	-1.80E+04	-1.80E+04	-1.80E+04
EI5	ADP elements	kg Sb-Equiv.	1.51E+04	1.51E+04	1.51E+04	1.51E+04	1.51E+04

EI6	ADP fossil	MJ	6.01E+12	6.01E+12	6.01E+12	6.01E+12	6.01E+12
EI7	FAETP inf.	kg DCB-Equiv.	-6.96E+08	-6.96E+08	-6.96E+08	-6.95E+08	-6.95E+08
EI8	HTP inf.	kg DCB-Equiv.	-4.21E+09	-4.21E+09	-4.21E+09	-4.21E+09	-4.21E+09
EI9	MAETP inf.	kg DCB-Equiv.	-2.94E+13	-2.94E+13	-2.94E+13	-2.94E+13	-2.94E+13
EI10	POCP	kg Etheme-Equiv.	5.33E+08	5.33E+08	5.33E+08	5.33E+08	5.33E+08
EI11	TETP inf.	kg DCB-Equiv.	4.76E+08	4.76E+08	4.76E+08	4.76E+08	4.76E+08
E12	Land occupation	m^3	6.93E+06	6.93E+06	6.93E+06	6.93E+06	6.93E+06

Table 6.2(e): Environmental impacts of scenario II (cont'd)

No.	Indicators	Unit	Scenario 2.21	Scenario 2.22	Scenario 2.23	Scenario 2.24	Scenario 2.25
EI1	GWP 100 years	kg CO2-Equiv.	2.75E+12	2.75E+12	2.75E+12	2.75E+12	2.75E+12
EI2	AP	kg SO2-Equiv.	4.57E+09	4.57E+09	4.57E+09	4.57E+09	4.57E+09
EI3	EP	kg Phosphate-Equiv.	2.85E+08	2.86E+08	2.86E+08	2.86E+08	2.86E+08
EI4	ODP, steady state	kg R11-Equiv.	-4.52E+04	-4.52E+04	-4.52E+04	-4.52E+04	-4.52E+04
EI5	ADP elements	kg Sb-Equiv.	1.12E+06	1.12E+06	1.12E+06	1.12E+06	1.12E+06
EI6	ADP fossil	MJ	1.73E+13	1.73E+13	1.73E+13	1.73E+13	1.73E+13
EI7	FAETP inf.	kg DCB-Equiv.	-8.46E+08	-8.46E+08	-8.45E+08	-8.45E+08	-8.45E+08
EI8	HTP inf.	kg DCB-Equiv.	1.73E+11	1.73E+11	1.73E+11	1.73E+11	1.73E+11
EI9	MAETP inf.	kg DCB-Equiv.	3.89E+14	3.89E+14	3.89E+14	3.89E+14	3.89E+14
EI10	POCP	kg Etheme-Equiv.	1.10E+09	1.10E+09	1.10E+09	1.10E+09	1.10E+09
EI11	TETP inf.	kg DCB-Equiv.	7.96E+08	7.96E+08	7.96E+08	7.96E+08	7.96E+08
E12	Land occupation	m^3	8.65E+06	8.65E+06	8.65E+06	8.65E+06	8.65E+06

6.3 Economic impacts of cross-regional mobility of C&D waste in Australia

6.3.1 Economic impacts of scenario 0.0 – base scenario

As presented in section 4.4.6, scenario 0.0 is developed based on the current practice of C&D waste management in Australia and used as the base scenario for scenario analysis. In general, 69.2% of managed waste is recycled intra-regionally, 0.6% of managed waste is recycled cross-regionally, 0.2% of managed waste is energy recovered intra-regionally, non-managed waste is energy recovered cross-regionally, 23.6% of managed waste is landfilled intra-regionally, and 6.4% of managed waste is landfilled cross-regionally. For each waste material, the rates of treatment vary. The details of scenario 0.0 are provided in section 4.4.6 in Chapter 4.

Based on the methods presented in section 4.4 (Chapter 4), economic impacts in terms of industry income for C&D waste generation in Australia in 2017 in scenario 0.0 are shown in Figure 6.17 and their value is shown in Table A-6.3 in Appendix B. It is found that the total industry income of managing waste is 6.95 billion AUD. Within that income, waste collection and transportation and pre-processing contributed 3.62 billion AUD. The income from recycling contributed 2.71 billion AUD, which includes recycling of masonry materials (1.37 billion AUD), recycling of metals (0.90 billion AUD), recycling of timber (79.8 million AUD), recycling of paper and cardboard (1.88 million AUD), recycling of plastics (3.23 million AUD), recycling of glass (1.78 million AUD) and recycling of other unclassified waste (0.25 billion AUD). The landfilling of waste contributed 0.61 billion AUD.

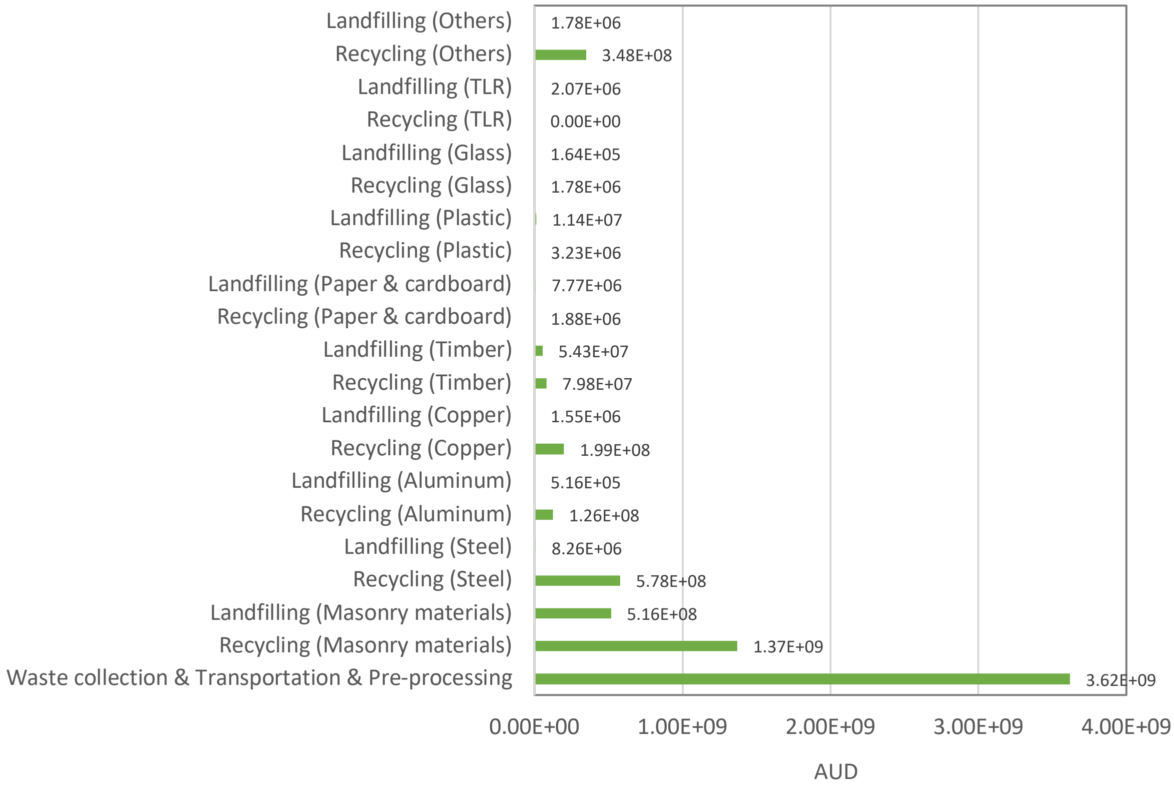


Figure 6.17: Economic impacts for C&D waste generated in Australia in 2017 (scenario 0.0)

6.3.2 Economic impacts of scenario I

As discussed in section 4.4.6 (Chapter 4), scenario setting I for treatment and disposal options will not consider energy recovery, but will consider recycling and landfilling (cross-regional mobility +, recycling rate +, No energy recovery). In scenario setting I, there are 25 scenarios from scenario 1.1 to scenario 1.25, developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, the recycling rate will be increased every 25% from 0% to 95%while the landfilling rate will be decreased from 100% to 5% accordingly. The percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%. Scenario setting I details are shown in section 4.4.6 in Chapter 4.

Based on the methods presented in section 4.4 in Chapter 4, economic impacts in terms of industry income for generated C&D waste in Australia in 2017 in scenario setting I are shown in Table 6.3. The results show the total industry income of treating generated C&D waste in scenario 1.1 to scenario 1.5 is 5.63 billion AUD. The value of Scenario 1.6 to Scenario 1.10 is 6.01 billion AUD; the value of scenario 1.11 to scenario 1.15 is 6.40 billion AUD; the value of scenario 1.16 to scenario 1.20 is 6.79 billion AUD; and the value of scenario 1.21 to scenario 1.22 is 7.10 billion AUD. If checked against original results, there are minor differences for scenario 1.1 to scenario 1.5; scenario 1.6 to scenario 1.10; scenario 1.11 to scenario 1.15; scenario 1.16 to scenario 1.20; and scenario 1.20 to scenario 1.25. The values in Table 6.3 do not show the difference due to scientific notation rules.

Table 6.3(a): Economic impacts of Scenario I (unit: AUD)

Waste	Activity	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.68E+09	1.68E+09	1.68E+09	1.68E+09	1.68E+09
Steel	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.05E+08	1.05E+08	1.05E+08	1.05E+08	1.05E+08
Aluminium	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	6.54E+06	6.54E+06	6.54E+06	6.54E+06	6.54E+06
Copper	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.96E+07	1.96E+07	1.96E+07	1.96E+07	1.96E+07
Organics (Timber)	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	9.77E+07	9.77E+07	9.77E+07	9.77E+07	9.77E+07
Paper & cardboard	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	9.65E+06	9.65E+06	9.65E+06	9.65E+06	9.65E+06
Plastics	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+07	1.30E+07	1.30E+07	1.30E+07	1.30E+07
Glass	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.65E+06	1.65E+06	1.65E+06	1.65E+06	1.65E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	2.60E+06	2.60E+06	2.60E+06	2.60E+06	2.60E+06
Others	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	7.82E+07	7.82E+07	7.82E+07	7.82E+07	7.82E+07
Total		**5.63E+09**	**5.63E+09**	**5.63E+09**	**5.63E+09**	**5.63E+09**

Table 6.3(b): Economic impacts of Scenario I (unit: AUD) (cont'd)

Waste	Activity	Scenario 1.6	Scenario 1.7	Scenario 1.8	Scenario 1.9	Scenario 1.10
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	4.94E+08	4.94E+08	4.94E+08	4.94E+08	4.94E+08
	Landfilling	1.26E+09	1.26E+09	1.26E+09	1.26E+09	1.26E+09
Steel	Recycling	1.57E+08	1.57E+08	1.57E+08	1.57E+08	1.57E+08
	Landfilling	7.84E+07	7.84E+07	7.84E+07	7.84E+07	7.84E+07
Aluminium	Recycling	3.43E+07	3.43E+07	3.43E+07	3.43E+07	3.43E+07
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06

Copper	Recycling	5.39E+07	5.39E+07	5.39E+07	5.39E+07	5.39E+07
	Landfilling	1.47E+07	1.47E+07	1.47E+07	1.47E+07	1.47E+07
Organics (Timber)	Recycling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
	Landfilling	7.32E+07	7.32E+07	7.32E+07	7.32E+07	7.32E+07
Paper & cardboard	Recycling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
	Landfilling	7.23E+06	7.23E+06	7.23E+06	7.23E+06	7.23E+06
Plastics	Recycling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
	Landfilling	9.76E+06	9.76E+06	9.76E+06	9.76E+06	9.76E+06
Glass	Recycling	4.95E+05	4.95E+05	4.95E+05	4.95E+05	4.95E+05
	Landfilling	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.95E+06	1.95E+06	1.95E+06	1.95E+06	1.95E+06
Others	Recycling	8.89E+07	8.89E+07	8.89E+07	8.89E+07	8.89E+07
	Landfilling	5.87E+07	5.87E+07	5.87E+07	5.87E+07	5.87E+07
Total		**6.01E+09**	**6.01E+09**	**6.01E+09**	**6.01E+09**	**6.01E+09**

Table 6.3(c): Economic impacts of Scenario I (unit: AUD)(cont'd)

Waste	Activity	Scenario 1.11	Scenario 1.12	Scenario 1.13	Scenario 1.14	Scenario 1.15
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	9.89E+08	9.89E+08	9.89E+08	9.89E+08	9.89E+08
	Landfilling	8.38E+08	8.38E+08	8.38E+08	8.38E+08	8.38E+08
Steel	Recycling	3.14E+08	3.14E+08	3.14E+08	3.14E+08	3.14E+08
	Landfilling	5.23E+07	5.23E+07	5.23E+07	5.23E+07	5.23E+07
Aluminium	Recycling	6.86E+07	6.86E+07	6.86E+07	6.86E+07	6.86E+07
	Landfilling	3.27E+06	3.27E+06	3.27E+06	3.27E+06	3.27E+06
Copper	Recycling	1.08E+08	1.08E+08	1.08E+08	1.08E+08	1.08E+08
	Landfilling	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06
Organics (Timber)	Recycling	9.77E+07	9.77E+07	9.77E+07	9.77E+07	9.77E+07
	Landfilling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
Paper & cardboard	Recycling	9.65E+06	9.65E+06	9.65E+06	9.65E+06	9.65E+06
	Landfilling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
Plastics	Recycling	1.30E+07	1.30E+07	1.30E+07	1.30E+07	1.30E+07
	Landfilling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
Glass	Recycling	9.90E+05	9.90E+05	9.90E+05	9.90E+05	9.90E+05
	Landfilling	8.25E+05	8.25E+05	8.25E+05	8.25E+05	8.25E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+06	1.30E+06	1.30E+06	1.30E+06	1.30E+06
Others	Recycling	1.78E+08	1.78E+08	1.78E+08	1.78E+08	1.78E+08
	Landfilling	3.91E+07	3.91E+07	3.91E+07	3.91E+07	3.91E+07
Total		**6.40E+09**	**6.40E+09**	**6.40E+09**	**6.40E+09**	**6.40E+09**

Table 6.3(d): Economic impacts of Scenario I (unit: AUD) (cont'd)

Waste	Activity	Scenario 1.16	Scenario 1.17	Scenario 1.18	Scenario 1.19	Scenario 1.20
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.48E+09	1.48E+09	1.48E+09	1.48E+09	1.48E+09
	Landfilling	4.19E+08	4.19E+08	4.19E+08	4.19E+08	4.19E+08
Steel	Recycling	4.71E+08	4.71E+08	4.71E+08	4.71E+08	4.71E+08
	Landfilling	2.61E+07	2.61E+07	2.61E+07	2.61E+07	2.61E+07
Aluminium	Recycling	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08
	Landfilling	1.63E+06	1.63E+06	1.63E+06	1.63E+06	1.63E+06
Copper	Recycling	1.62E+08	1.62E+08	1.62E+08	1.62E+08	1.62E+08
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06
Organics (Timber)	Recycling	1.46E+08	1.46E+08	1.46E+08	1.46E+08	1.46E+08
	Landfilling	2.44E+07	2.44E+07	2.44E+07	2.44E+07	2.44E+07
Paper & cardboard	Recycling	1.45E+07	1.45E+07	1.45E+07	1.45E+07	1.45E+07
	Landfilling	2.41E+06	2.41E+06	2.41E+06	2.41E+06	2.41E+06
Plastics	Recycling	1.95E+07	1.95E+07	1.95E+07	1.95E+07	1.95E+07
	Landfilling	3.25E+06	3.25E+06	3.25E+06	3.25E+06	3.25E+06
Glass	Recycling	1.48E+06	1.48E+06	1.48E+06	1.48E+06	1.48E+06
	Landfilling	4.12E+05	4.12E+05	4.12E+05	4.12E+05	4.12E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	6.50E+05	6.50E+05	6.50E+05	6.50E+05	6.50E+05
Others	Recycling	2.67E+08	2.67E+08	2.67E+08	2.67E+08	2.67E+08
	Landfilling	1.96E+07	1.96E+07	1.96E+07	1.96E+07	1.96E+07
Total		**6.79E+09**	**6.79E+09**	**6.79E+09**	**6.79E+09**	**6.79E+09**

Table 6.3(e): Economic impacts of Scenario I (unit: AUD)(cont'd)

Waste	Activity	Scenario 1.21	Scenario 1.22	Scenario 1.23	Scenario 1.24	Scenario 1.25
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.88E+09	1.88E+09	1.88E+09	1.88E+09	1.88E+09
	Landfilling	8.38E+07	8.38E+07	8.38E+07	8.38E+07	8.38E+07
Steel	Recycling	5.96E+08	5.96E+08	5.96E+08	5.96E+08	5.96E+08
	Landfilling	5.23E+06	5.23E+06	5.23E+06	5.23E+06	5.23E+06
Aluminium	Recycling	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08
	Landfilling	3.27E+05	3.27E+05	3.27E+05	3.27E+05	3.27E+05
Copper	Recycling	2.05E+08	2.05E+08	2.05E+08	2.05E+08	2.05E+08
	Landfilling	9.81E+05	9.81E+05	9.81E+05	9.81E+05	9.81E+05
Organics (Timber)	Recycling	1.86E+08	1.86E+08	1.86E+08	1.86E+08	1.86E+08
	Landfilling	4.88E+06	4.88E+06	4.88E+06	4.88E+06	4.88E+06
Paper & cardboard	Recycling	1.83E+07	1.83E+07	1.83E+07	1.83E+07	1.83E+07

	Landfilling	4.82E+05	4.82E+05	4.82E+05	4.82E+05	4.82E+05
Plastics	Recycling	2.47E+07	2.47E+07	2.47E+07	2.47E+07	2.47E+07
	Landfilling	6.51E+05	6.51E+05	6.51E+05	6.51E+05	6.51E+05
Glass	Recycling	1.88E+06	1.88E+06	1.88E+06	1.88E+06	1.88E+06
	Landfilling	8.25E+04	8.25E+04	8.25E+04	8.25E+04	8.25E+04
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05
Others	Recycling	3.38E+08	3.38E+08	3.38E+08	3.38E+08	3.38E+08
	Landfilling	3.91E+06	3.91E+06	3.91E+06	3.91E+06	3.91E+06
Total		**7.10E+09**	**7.10E+09**	**7.10E+09**	**7.10E+09**	**7.10E+09**

6.3.3 Economic impacts of scenario II

As discussed in section 4.4.6 (Chapter 4), scenario setting II for treatment and disposal options will not consider energy recovery, but will consider recycling and landfilling (cross-regional mobility +, recycling rate -, No energy recovery). In scenario setting II, there are 25 scenarios from scenario 2.1 to scenario 2.25 developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, the recycling rate will be decreased every 25% from 95% to 0% while the landfilling rate will be increased from 5% to 100% accordingly. The percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%. Scenario setting II details are shown in section 4.4.6 in Chapter 4.

Based on the methods presented in Chapter 4, economic impacts in terms of industry income for generated C&D waste in Australia in scenario setting II is shown in Table 6.4. The results show the total industry income of treating generated C&D waste in each scenario from scenario 2.1 to scenario 2.5 is 7.10 billion AUD. The value of scenario 2.6 to scenario 2.10 is 6.79 billion AUD; the value of scenario 1.11 to scenario 1.15 is 6.4 billion AUD; the value of scenario 1.16 to scenario 1.20 is 6.01 billion AUD; the value of scenario 1.21 to scenario 1.22 is 5.70 billion AUD.

Table 6.4(a): Economic impacts of scenario II (unit: AUD)

Waste	Activity	Scenario 2.1	Scenario 2.2	Scenario 2.3	Scenario 2.4	Scenario 2.5
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.88E+09	1.88E+09	1.88E+09	1.88E+09	1.88E+09
	Landfilling	8.38E+07	8.38E+07	8.38E+07	8.38E+07	8.38E+07
Steel	Recycling	5.96E+08	5.96E+08	5.96E+08	5.96E+08	5.96E+08
	Landfilling	5.23E+06	5.23E+06	5.23E+06	5.23E+06	5.23E+06

Aluminium	Recycling	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08
	Landfilling	3.27E+05	3.27E+05	3.27E+05	3.27E+05	3.27E+05
Copper	Recycling	2.05E+08	2.05E+08	2.05E+08	2.05E+08	2.05E+08
	Landfilling	9.81E+05	9.81E+05	9.81E+05	9.81E+05	9.81E+05
Organics (Timber)	Recycling	1.86E+08	1.86E+08	1.86E+08	1.86E+08	1.86E+08
	Landfilling	4.88E+06	4.88E+06	4.88E+06	4.88E+06	4.88E+06
Paper & cardboard	Recycling	1.83E+07	1.83E+07	1.83E+07	1.83E+07	1.83E+07
	Landfilling	4.82E+05	4.82E+05	4.82E+05	4.82E+05	4.82E+05
Plastics	Recycling	2.47E+07	2.47E+07	2.47E+07	2.47E+07	2.47E+07
	Landfilling	6.51E+05	6.51E+05	6.51E+05	6.51E+05	6.51E+05
Glass	Recycling	1.88E+06	1.88E+06	1.88E+06	1.88E+06	1.88E+06
	Landfilling	8.25E+04	8.25E+04	8.25E+04	8.25E+04	8.25E+04
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05
Others	Recycling	3.38E+08	3.38E+08	3.38E+08	3.38E+08	3.38E+08
	Landfilling	3.91E+06	3.91E+06	3.91E+06	3.91E+06	3.91E+06
Total		**7.10E+09**	**7.10E+09**	**7.10E+09**	**7.10E+09**	**7.10E+09**

Table 6.4(b): Economic impacts of Scenario II (unit: AUD) (cont'd)

Waste	Activity	Scenario 2.6	Scenario 2.7	Scenario 2.8	Scenario 2.9	Scenario 2.10
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.48E+09	1.48E+09	1.48E+09	1.48E+09	1.48E+09
	Landfilling	4.19E+08	4.19E+08	4.19E+08	4.19E+08	4.19E+08
Steel	Recycling	4.71E+08	4.71E+08	4.71E+08	4.71E+08	4.71E+08
	Landfilling	2.61E+07	2.61E+07	2.61E+07	2.61E+07	2.61E+07
Aluminium	Recycling	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08
	Landfilling	1.63E+06	1.63E+06	1.63E+06	1.63E+06	1.63E+06
Copper	Recycling	1.62E+08	1.62E+08	1.62E+08	1.62E+08	1.62E+08
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06
Organics (Timber)	Recycling	1.46E+08	1.46E+08	1.46E+08	1.46E+08	1.46E+08
	Landfilling	2.44E+07	2.44E+07	2.44E+07	2.44E+07	2.44E+07
Paper & cardboard	Recycling	1.45E+07	1.45E+07	1.45E+07	1.45E+07	1.45E+07
	Landfilling	2.41E+06	2.41E+06	2.41E+06	2.41E+06	2.41E+06
Plastics	Recycling	1.95E+07	1.95E+07	1.95E+07	1.95E+07	1.95E+07
	Landfilling	3.25E+06	3.25E+06	3.25E+06	3.25E+06	3.25E+06
Glass	Recycling	1.48E+06	1.48E+06	1.48E+06	1.48E+06	1.48E+06
	Landfilling	4.12E+05	4.12E+05	4.12E+05	4.12E+05	4.12E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	6.50E+05	6.50E+05	6.50E+05	6.50E+05	6.50E+05
Others	Recycling	2.67E+08	2.67E+08	2.67E+08	2.67E+08	2.67E+08

	Landfilling	1.96E+07	1.96E+07	1.96E+07	1.96E+07	1.96E+07
Total		**6.79E+09**	**6.79E+09**	**6.79E+09**	**6.79E+09**	**6.79E+09**

Table 6.4(c): Economic impacts of Scenario II (unit: AUD)(cont'd)

Waste	Activity	Scenario 2.11	Scenario 2.12	Scenario 2.13	Scenario 2.14	Scenario 2.15
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	9.89E+08	9.89E+08	9.89E+08	9.89E+08	9.89E+08
	Landfilling	8.38E+08	8.38E+08	8.38E+08	8.38E+08	8.38E+08
Steel	Recycling	3.14E+08	3.14E+08	3.14E+08	3.14E+08	3.14E+08
	Landfilling	5.23E+07	5.23E+07	5.23E+07	5.23E+07	5.23E+07
Aluminium	Recycling	6.86E+07	6.86E+07	6.86E+07	6.86E+07	6.86E+07
	Landfilling	3.27E+06	3.27E+06	3.27E+06	3.27E+06	3.27E+06
Copper	Recycling	1.08E+08	1.08E+08	1.08E+08	1.08E+08	1.08E+08
	Landfilling	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06
Organics (Timber)	Recycling	9.77E+07	9.77E+07	9.77E+07	9.77E+07	9.77E+07
	Landfilling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
Paper & cardboard	Recycling	9.65E+06	9.65E+06	9.65E+06	9.65E+06	9.65E+06
	Landfilling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
Plastics	Recycling	1.30E+07	1.30E+07	1.30E+07	1.30E+07	1.30E+07
	Landfilling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
Glass	Recycling	9.90E+05	9.90E+05	9.90E+05	9.90E+05	9.90E+05
	Landfilling	8.25E+05	8.25E+05	8.25E+05	8.25E+05	8.25E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+06	1.30E+06	1.30E+06	1.30E+06	1.30E+06
Others	Recycling	1.78E+08	1.78E+08	1.78E+08	1.78E+08	1.78E+08
	Landfilling	3.91E+07	3.91E+07	3.91E+07	3.91E+07	3.91E+07
Total		**6.40E+09**	**6.40E+09**	**6.40E+09**	**6.40E+09**	**6.40E+09**

Table 6.4(d): Economic impacts of Scenario II (unit: AUD)(cont'd)

Waste	Activity	Scenario 2.16	Scenario 2.17	Scenario 2.18	Scenario 2.19	Scenario 2.20
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	4.94E+08	4.94E+08	4.94E+08	4.94E+08	4.94E+08
	Landfilling	1.26E+09	1.26E+09	1.26E+09	1.26E+09	1.26E+09
Steel	Recycling	1.57E+08	1.57E+08	1.57E+08	1.57E+08	1.57E+08
	Landfilling	7.84E+07	7.84E+07	7.84E+07	7.84E+07	7.84E+07
Aluminium	Recycling	3.43E+07	3.43E+07	3.43E+07	3.43E+07	3.43E+07
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06
Copper	Recycling	5.39E+07	5.39E+07	5.39E+07	5.39E+07	5.39E+07
	Landfilling	1.47E+07	1.47E+07	1.47E+07	1.47E+07	1.47E+07

Organics (Timber)	Recycling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
	Landfilling	7.32E+07	7.32E+07	7.32E+07	7.32E+07	7.32E+07
Paper & cardboard	Recycling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
	Landfilling	7.23E+06	7.23E+06	7.23E+06	7.23E+06	7.23E+06
Plastics	Recycling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
	Landfilling	9.76E+06	9.76E+06	9.76E+06	9.76E+06	9.76E+06
Glass	Recycling	4.95E+05	4.95E+05	4.95E+05	4.95E+05	4.95E+05
	Landfilling	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.95E+06	1.95E+06	1.95E+06	1.95E+06	1.95E+06
Others	Recycling	8.89E+07	8.89E+07	8.89E+07	8.89E+07	8.89E+07
	Landfilling	5.87E+07	5.87E+07	5.87E+07	5.87E+07	5.87E+07
Total		**6.01E+09**	**6.01E+09**	**6.01E+09**	**6.01E+09**	**6.01E+09**

Table 6.4(e): Economic impacts of Scenario II (unit: AUD)(cont'd)

Waste	Activity	Scenario 2.21	Scenario 2.22	Scenario 2.23	Scenario 2.24	Scenario 2.25
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	9.89E+07	9.89E+07	9.89E+07	9.89E+07	9.89E+07
	Landfilling	1.59E+09	1.59E+09	1.59E+09	1.59E+09	1.59E+09
Steel	Recycling	3.14E+07	3.14E+07	3.14E+07	3.14E+07	3.14E+07
	Landfilling	9.94E+07	9.94E+07	9.94E+07	9.94E+07	9.94E+07
Aluminium	Recycling	6.86E+06	6.86E+06	6.86E+06	6.86E+06	6.86E+06
	Landfilling	6.21E+06	6.21E+06	6.21E+06	6.21E+06	6.21E+06
Copper	Recycling	1.08E+07	1.08E+07	1.08E+07	1.08E+07	1.08E+07
	Landfilling	1.86E+07	1.86E+07	1.86E+07	1.86E+07	1.86E+07
Organics (Timber)	Recycling	9.77E+06	9.77E+06	9.77E+06	9.77E+06	9.77E+06
	Landfilling	9.28E+07	9.28E+07	9.28E+07	9.28E+07	9.28E+07
Paper & cardboard	Recycling	9.65E+05	9.65E+05	9.65E+05	9.65E+05	9.65E+05
	Landfilling	9.16E+06	9.16E+06	9.16E+06	9.16E+06	9.16E+06
Plastics	Recycling	1.30E+06	1.30E+06	1.30E+06	1.30E+06	1.30E+06
	Landfilling	1.24E+07	1.24E+07	1.24E+07	1.24E+07	1.24E+07
Glass	Recycling	9.90E+04	9.90E+04	9.90E+04	9.90E+04	9.90E+04
	Landfilling	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	2.47E+06	2.47E+06	2.47E+06	2.47E+06	2.47E+06
Others	Recycling	1.78E+07	1.78E+07	1.78E+07	1.78E+07	1.78E+07
	Landfilling	7.43E+07	7.43E+07	7.43E+07	7.43E+07	7.43E+07
Total		**5.70E+09**	**5.70E+09**	**5.70E+09**	**5.70E+09**	**5.70E+09**

6.4 Social impacts of cross-regional mobility of C&D waste in Australia

Based on the data and assessment methods presented in section 4.4 (Chapter 4), social impacts in terms of employment (unit: p full-time equivalent) of cross-regional mobility of C&D waste based on the 2017 Australian data have been calculated, and the general findings (employment impacts) are shown in Figure 6.18. (The data in Figure 6.18 can be found in Table A-6.4 in Appendix B.) It is found that ACT, VIC and QLD have gained 328.17 p, 12.19 p, and 305.71 p full-time equivalent respectively while NSW, SA and WA have lost 958.11 p, 29.09 p and 4.88 p full-time equivalent due to cross-regional mobility of C&D waste. Cross-regional transformation of social impacts is shown in Figure 6.19.

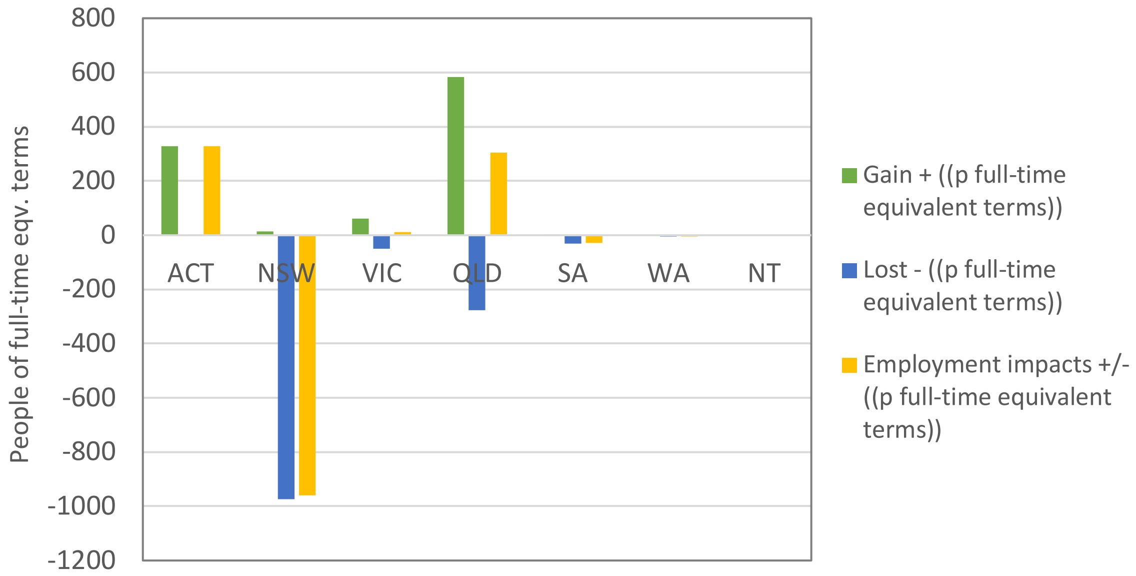


Figure 6.18: Employment impacts of cross-regional mobility of C&D waste (based on Australian waste generation data in 2017)

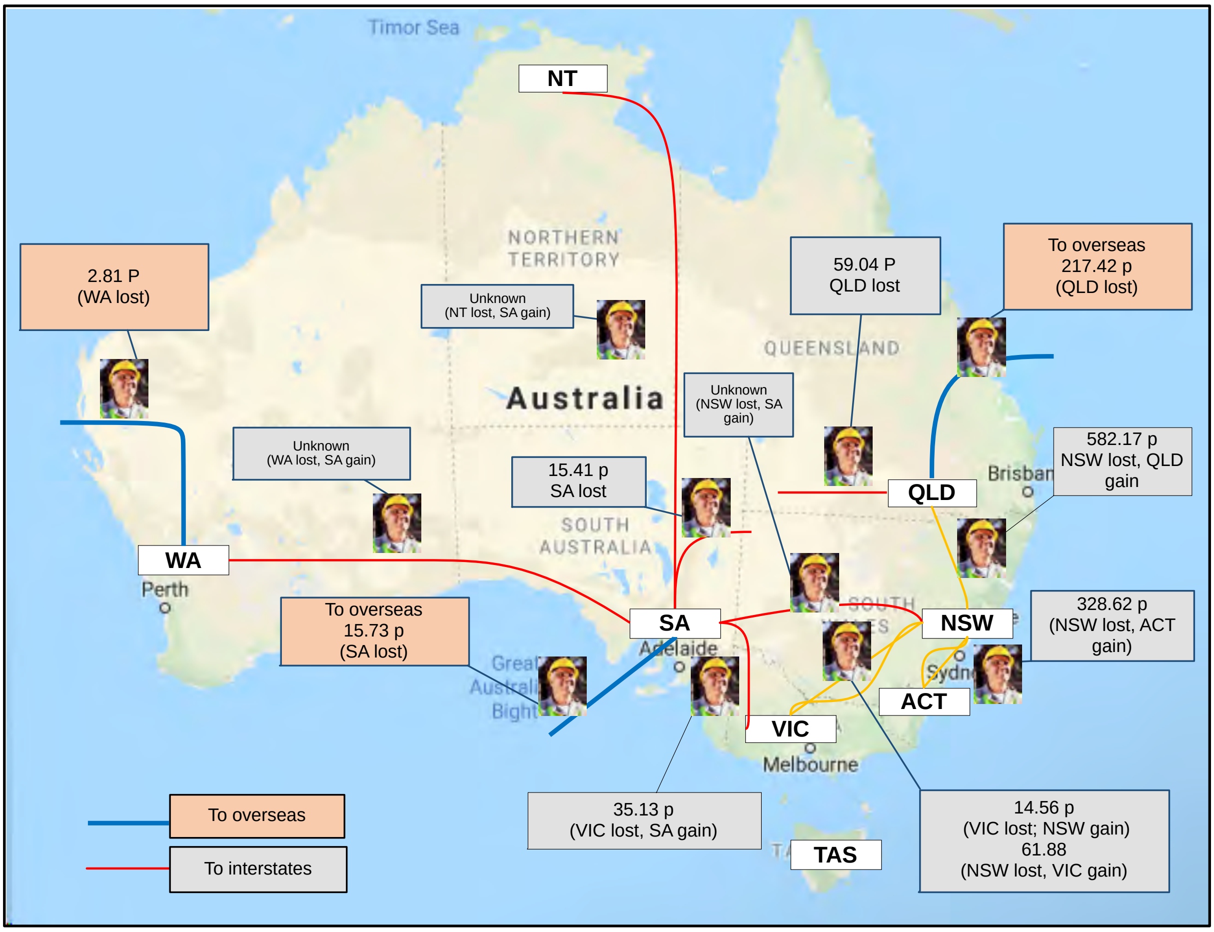


Figure 6.19: Employment transferring of cross-regional mobility of C&D waste (based on Australian waste generation data in 2017)

To be specific, VIC transported 16,000 t (0.3%) of masonry waste to NSW. As a result, VIC lost but NSW gained 14.56 p full-time equivalent; VIC transported C&D waste materials including metals 32,985 t (25%), paper and cardboard 2,374 t (46%), plastics 2,074 t (74%), TLR 445t (45%), glass 75t (7%), organics 656 t (1%) of recovered C&D waste interstate (SA), hence VIC lost 35.13 p full-time equivalent; NSW transported 68,000 tons of masonry waste to VIC, hence NSW lost but VIC gains 61.88 p full-time equivalent; NSW transported 561,118 t of masonry waste to ACT, hence NSW lost but ACT gained 328.62 p full-time equivalent; NSW transported 639, 747 t of masonry waste QLD, hence NSW lost but QLD gained 582.17 p full-time equivalent; QLD transported masonry materials 243 t (<0.1%), metals 64,516 t (26%), plastics 71 t (33%), TLR 53t (<1%) of recovered C&D waste interstate, hence QLD lost 59.04 p full-time equivalent; SA transported 14,981 (48%) metals, 1,954 t (48%) plastics, hence SA lost 15.41 p full-time equivalent; WA transported 2,237 t (2%) metals and 11 t (<1%) paper and cardboard to SA. As a result, WA lost but SA gained 2.05 p full-time equivalent.

Regarding overseas, QLD exported 237,725 t (75%) metals waste and 1,203 t (55%) plastics overseas, hence QLD lost 217.42 p full-time equivalent; SA exported 15, 293 t (49%) metals and 1,995 t (49%) plastics overseas, hence SA lost 15.73 p full-time equivalent; WA exported 2, 237 t (2%) metals and 877 t (99%) paper and cardboard overseas, hence WA lost 2.83 p full-time equivalent. Results of social impacts in terms of employment of cross-regional mobility of C&D waste based on Australian waste generation data in 2017 are shown in Table 6.5.

Table 6.5: Social impacts of cross-regional mobility of C&D waste (based on Australian waste generation data in 2017)

Cross-regional mobility		Cross-regional mobility data	Treatment methods	Base scenario (p full-time equivalent)	Explanation
From	**To**				
Cross-regional mobility of C&D waste generated (interstate)					
VIC	NSW	16,000 t (0.3%) of masonry waste	Landfilling	14.56	VIC lost; NSW gain
VIC	SA	Metals 32,985 t (25%), paper & cardboard 2,374 t (46%), plastics 2,074 t (74%), TLR 445 t (45), glass 75 t (7%), and organics 656 t (1%) of recovered C&D waste	Recycling	35.13	VIC lost; SA gain
NSW	VIC	68,000 t of masonry waste	Landfilling	61.88	NSW lost; VIC gain
NSW	ACT	561,118 t of masonry waste	Landfilling	328.62	NSW lost; ACT gain
NSW	QLD	639, 747 t masonry waste	Landfilling	582.17	NSW lost, QLD gain
QLD	Interstate	Masonry materials 243 t (<0.1%), metals 64,516 t (26%), plastics 71 t (33%), TLR 53 t (<1%) of recovered C&D waste	Recycling	59.04	QLD lost
SA	Interstate	14,981 (48%) metals and 1,954 t (48%) plastics	Recycling	15.41	SA lost
WA	SA	2,237 t (2%) metals, 11 t (<1%) paper & cardboard, and glass (unknown amount)	Recycling	2.05	WA lost, SA gain
Cross-regional mobility of C&D waste generated (overseas)					
QLD	Overseas	237,725 t (75%) metals waste and 1,203 t (55%) plastics	Recycling	217.42	QLD lost
SA	Overseas	15, 293 t (49%) metals and 1, 995 t (49%) plastics	Recycling	15.73	SA lost
WA	Overseas	2, 237 t (2%) metals and 877 t (99%) paper & cardboard materials	Recycling	2.83	WA lost

6.5 Summary

This chapter presented the results of impacts of cross-regional mobility of C&D waste in Australia. The results included the environmental impacts of cross-regional mobility, economic impacts of cross-regional mobility, and social impacts of cross-regional mobility of C&D waste in Australia.

Based on calculations for environmental impacts for currently generated C&D waste included GWP 100 years (-6.73E+11 kg CO2-Equiv.), AP (-2.92E+09 kg SO2-Equiv.), EP (-5.18E+07 kg Phosphate-Equiv.), ODP (4.06E+04 kg R11-Equiv.), ADP elements (-8.75E+05 kg Sb-Equiv.), ADP fossil (-1.34E+13 MJ), FAETP inf. (1.82E+09 kg DCB-Equiv.), HTP inf. (-1.09E+11 kg DCB-Equiv.), MAETP inf. (-3.01E+14 kg DCB-Equiv.), POCP (-5.10E+08 kg Etheme-Equiv.), TETP inf. (1.15E+09 kg DCB-Equiv.) and Land occupation (3.55E+06 m3). Environmental impacts of scenario I and scenario II respectively have also been evaluated.

Based on calculations for economic impacts, it was found that industry income from managing waste was 6.95 billion AUD base scenario. Waste collection and transportation and pre-processing contributed 3.62 billion AUD. Income from recycling contributed 2.71 billion AUD, which included recycling masonry materials (1.37 billion AUD), recycling metals (0.90 billion AUD), recycling timber (79.8 million AUD), recycling paper and cardboard (1.88 million AUD), recycling plastics (3.23 million AUD), recycling glass (1.78 million AUD) and recycling other unclassified waste (0.25 billion AUD). The landfilling of waste contributed 0.61 billion AUD. Economic impacts of scenario I and scenario II respectively have also been evaluated.

Based on calculations, cross-regional mobility of C&D waste has social impacts in terms of employment in states and territories in Australia. For instance, ACT, VIC and QLD gained 328.17 p, 12.19 p, and 305.71 p full-time equivalent respectively; NSW, SA and WA lost 958.11 p, 29.09 p, and 4.88 p full-time equivalent respectively.

Chapter 7. Discussion

7.1 Introduction

This chapter presents discussion based on research findings. The chapter consists of three main parts: characterisation of cross-regional mobility of C&D waste in Australia; impacts of C&D waste cross-regional mobility in Australia; and recommended optimisation strategies regarding the management of cross-regional mobility of C&D waste in Australia. The first part presents a discussion of C&D waste and recycling in Australia, C&D waste cross-regional mobility in Australia, and drivers of cross-regional mobility of C&D waste in Australia. **The contents of this section have been published in associated publication 1 listed on page xiii**. The second part presents a discussion of the environmental impacts of C&D waste cross-regional mobility in Australia, economic impacts of C&D waste cross-regional mobility in Australia, and social impacts of C&D waste cross-regional mobility in Australia. A series of optimisation strategies for the management of cross-regional mobility of C&D waste in Australia is also discussed, followed by recommendations for optimisation strategies.

7.2 Characterisation of cross-regional mobility of C&D waste in Australia

This section discusses the characterisation of cross-regional mobility of C&D waste in Australia based on the results outlined in Chapter 5. It starts with a brief discussion of C&D waste management and recycling in Australia by comparing three main solid waste streams. It goes on to discuss the management and recycling of critical C&D waste materials. It then discusses cross-regional mobility of C&D waste in Australia with respect to critical regions and waste materials and concludes with a discussion about the drivers of cross-regional mobility.

7.2.1 C&D waste management and recycling in Australia

7.2.1.1 Comparing C&D waste management with other waste streams

According to the *National Waste Report 2018*, solid waste in Australia is mainly generated from three sectors, namely municipal solid waste (MSW), construction and development (C&D) waste, and commercial and industrial (C&I) core waste. C&D waste is the largest waste stream and contributed about 37% of total waste generation in Australia in 2017 (Figure 7.1). Defined by Dee (2018), MSW refers to waste produced primarily by households and council operations; C&D waste refers to waste produced by building and demolition activities, including road and rail construction and maintenance and excavation of land associated with construction activities; C&I waste refers to waste produced by institutions and businesses; and includes waste from schools, restaurants, offices, retail and wholesale businesses, and industries such as manufacturing.

The characterisations of these waste types and related management processes are very different in Australia. For MSW, every household has three waste bins for this type of waste (i.e., one bin for garden waste, one for recyclable waste, and one for general waste), and these bins are collected regularly by city councils. The management of C&D waste are more complex, and waste collection plans are based on individual situations of construction sites. For instance, C&D waste bins will be put on construction sites to collect waste, and when full the waste bin will be collected by a C&D waste processor (i.e. a company providing C&D waste bin delivery and collection services, some of whom may also conduct a primary sorting of the waste) for further treatment. In addition to generating more waste and its greater complexity, C&D waste also involves more stakeholders and management processes than its competitors. Hence, the management of C&D waste constitutes a critical sector of waste management in Australia.

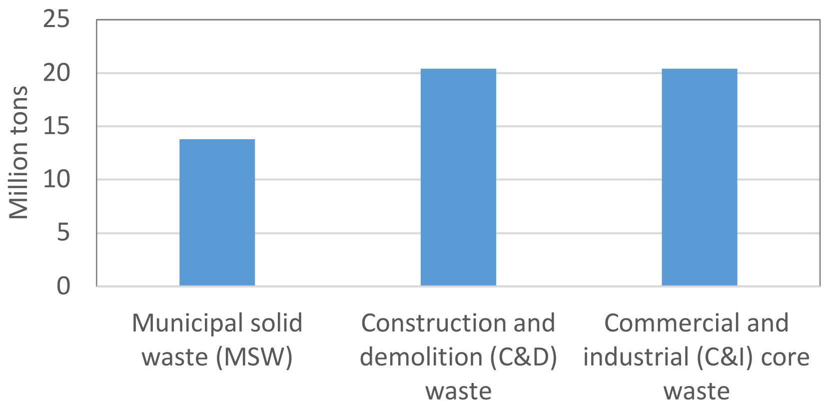


Figure 7.1: Solid waste generated in Australia in 2017

7.2.1.2 Management and recycling of critical C&D waste materials

As presented in section 5.2, C&D waste mainly comprises eight categories of wastes; including masonry materials (e.g., asphalt, bricks, concrete, rubble, plasterboard, and cement sheeting), Metals (e.g., steel, aluminium, and other non-ferrous materials), organics (e.g., garden organics and timber), paper and cardboard, plastics, glass, textiles, and other unclassified materials. The weight contributions of these waste materials vary dramatically, and the management of these waste materials are also different. For instance, most masonry waste is generated from the construction and demolition sectors, and masonry materials contribute about 83% of the total generated C&D waste by weight. The remaining waste materials are a composite mix of metals, plastics, organics, paper and cardboard, glass, etc. These materials are typically processed along with similar waste types generated from MSW and C&I waste sectors. Given this generation, an integrated waste management strategy could be applied to these types of waste, as an economic scale for waste treatment is a critical factor for feasibility of recycling.

As presented in section 5.2.2, the current recycling methods and recycling rates are dramatically different for various C&D waste materials. Based on analysis of the composition and fate of C&D waste in Australia; the overall recycling rates of metals and glass are above 90%. This is due to their value and the recycling market for such materials. The recycling rate of masonry materials is also relatively high. These materials can be converted into recycled aggregate and rubber and used as road and garden bases. The recycling of masonry materials is popular in industry, mainly because of a well-established market and the competitive pricing of recycled products. Similarly, some combustible materials such as organics, paper and cardboard, and TLR are in demand as an alternative fuel in the market, thereby expanding potential treatment methods for these waste materials. Hence, recycling strategies should be applied according to the recycling potential of waste materials. Similarly, industry should be encouraged to determine the best methods of recycling C&D waste material according to the economic outcomes emanating from a better-recycled products market.

7.2.2 C&D waste cross-regional mobility in Australia

Section 5.3 has presented three main forms of cross-regional mobility of C&D waste in Australia, namely transporting C&D waste interstate for recycling, transporting C&D waste interstate for landfilling, and transporting C&D waste overseas for reprocessing/recycling. Based on the findings in Chapter 5, this section will further discuss the recycling centre of cross-regional mobility of C&D waste in Australia, cross-regional mobility of C&D waste for landfilling at eastern regions in Australia, and critical C&D waste materials of cross-regional mobility.

7.2.2.1 Recycling centre of cross-regional mobility of C&D waste

In terms of states and territories involved in C&D waste cross-regional mobility, the research shows that South Australia (SA) is at the centre of waste cross-regional mobility for reprocessing/recycling in Australia, as many states or territories transport their waste to SA for reprocessing/recycling (detailed in section 5.3.1). There are many reasons for this trend, such as the well-established SA industry, good supply chains, good markets, appropriate regulations and business support from government. For instance, there is a number of well-known C&D waste recycling enterprises (like *ResouceCo*), based on South Australia, that have expanded their business to national level and occasionally overseas. Apart from the *Environmental Protection Agency*, SA also have Institutes such as Green Industries SA, an internationally recognised Institute for improving resource efficiency and business productivity that is under the control of the Government of South Australia, and works closely with both industry and academia with the aim to reduce consumption, waste and costs. Similarly, state and territory research and industry reports, indicate that the availability and level of detail of data in South Australian is better than many of its competitors. These factors all give credence to the view that South Australia is a well-established centre for waste recycling in Australia.

7.2.2.2 Cross-regional mobility of C&D waste for landfill in the eastern regions

The traditional expectation, based on the kind of heavy materials that make up C&D waste, is that C&D waste materials is sent as landfill to local facilities. The findings in 5.3.2, suggest that cross-regional mobility of C&D waste is quite dynamic in Australia's eastern regions of NSW, ACT, VIC and QLD. Masonry waste in particular, is normally processed or disposed of within the regions and involves cross-regional mobility between those areas. For example, a significant portion of masonry waste material in NSW was transported cross-border and used as landfill in bordering regions because the disposal fees in the adjoining region or state were dramatically lower than those in NSW. The C&D waste cross-regional mobility map of Australia (Figure 5.8 in section 5.3) clearly shows that there are some cross-regional routes between NSW and VIC, NSW and the ACT, NSW and QLD. As a consequence, NSW has become a major player in transporting its C&D waste, particularly masonry waste to its neighbours, where the adjoining states or territories have dramatically lower disposal fees. The reasons for this phenomenon can involve multiple factors such as facilities availability, landfill levy, etc. These are discussed in section 7.2.3.

7.2.2.3 Critical C&D waste materials of cross-regional mobility

Section 5.2 suggests that C & D waste comprises different materials, such as masonry, Metals, organics, and so on. However, not all C&D waste materials are involved in cross-regional mobility. Similarly, the C&D waste materials involved in cross-regional mobility are also different due to the characterisation of waste. For instance, although most masonry waste was processed or disposed of within the region where the waste was generated, a considerable amount of this kind of waste was also transported cross-border to landfill and a minor portion of waste was sent to other regions for reprocessing/recycling. Waste materials such as metals, plastics, and paper and cardboard are more likely to be reprocessed in other regions or even overseas, as there are well-established global trading networks for those types of waste materials. Accordingly, some C&D waste materials such as masonry waste, metals, plastics, and paper and cardboard should be paid more attention when adopting waste management strategies.

7.2.3 Drivers of cross-regional mobility of C&D waste in Australia

Chapter 5 suggests that there are three main forms of cross-regional mobility of C&D waste in Australia. There are many reasons for this including facilities availability, disposal cost, industry traditional practices, regulations, and so on. Section 4.2 dealing with the expert interviews and the expert seminar provides the background for the following discussion about the three main drivers of cross-regional mobility of C&D waste in Australia.

7.2.3.1 Facilities availability

In countries like Australia, which has a large land area but a relatively small population (25.5 million in 2019 – Australian Bureau of Statistics), the scale of remote cities or towns is usually insignificant. It is unrealistic for all cities or towns to have C&D waste management facilities. The availability of such facilities has become a critical catalyst for cross-regional mobility of C&D waste. As discussed in the expert seminar; in some instances, there are no recycling facilities for certain waste materials in a particular region. Hence, waste processors have to find a destination with recycling facilities. This leads to a common practice in which some C&D waste materials such as metal, plastics and glass have been transported from rural areas to metropolitan areas for further processing, particularly evident in the Victorian State-wide Waste and Resource Recovery Infrastructure Plan 2017 (SV, 2018a).

Due to geographical factors, in some border towns or cities, the closest waste management service (i.e. recycling facilities or landfill sites) are located on the other side of the border. Waste processors prefer to send waste to nearby cross-border regions for further processing or landfill, considering the cost savings on transportation (SV, 2018a; QG, 2019). Indeed, this type of cross-regional mobility can increase the rates of managed C&D waste, because if there is no appropriate waste management facility nearby, waste may be dumped illegally rather than recycled appropriately to landfill.

7.2.3.2 Avoiding/reducing landfill levy

As revealed in the expert seminar, avoiding/reducing the landfill levy is a critical reason for cross-regional mobility of disposing masonry waste outside the original generation region. This levy is in place to provide an incentive to divert materials from landfill and recover economic value. As presented in the results, moving C&D waste cross-border is not uncommon in eastern regions of Australia, where landfill levies are significantly different among regions. For instance, the landfill levy of C&D waste in the metropolitan region of NSW can be up to 140AUD/t, yet there is no landfill levy for this type of waste in the neighbouring ACT and QLD. *Note: The landfill levy for C&D waste was meant to be introduced in QLD from March 2019*. The landfill levy is the fee imposed by government. Normally, landfills will determine the landfill price according to waste compositions (see Table A-7.1 in Appendix B). Noted by the "Government officer (C&D waste management related)" in the expert seminar, differences in the landfill levy provide incentives to transporters to select cheaper cross-border landfill sites. Using cheaper landfill options interstate can give practitioners better economic outcomes; however it can undermine the governments' approach to waste management and resource recovery, and it can also undermine the local market (SV, 2018a).

7.2.3.3 Recycling industry market

Since Australia is a market-based economy and the Australian Constitution also enshrines freedom of trade between states and territories, the industry can determine C&D waste material steams flow to wherever the best economic outcomes can be achieved (Dee, 2018). "Although the waste processer will sometimes also transport the waste to their familiar downstream processer according to their traditional practice, they are most likely to send their waste materials to regions where there is a well-established recycling industry market", according to senior managers of two renowned C&D waste recyclers in SA. As evidenced in the findings in Chapter 5, although most C&D waste material streams and waste generated in each state or territory remains in situ for reprocessing and management, a significant amount of C&D waste materials has been transported cross-border for recycling, and some materials exported overseas.

7.3 Impacts of C&D waste cross-regional mobility in Australia

Based on the findings in Chapter 6, this section discusses the environmental, economic, and social impacts of cross-regional mobility of C&D waste in Australia using an impacts contribution analysis and scenario analysis. The impacts contribution analysis clearly identifies the most critical impacts of C&D waste cross-regional mobility in Australia; whilst the scenario analysis compares the difference of those impacts in various scenarios, thereby illustrating how cross-regional mobility of C&D waste affects the C&D waste management performance. These analyses can also inform the development of optimisation strategies for the management of cross-regional mobility of C&D waste.

7.3.1 Environmental impacts of C&D waste cross-regional mobility in Australia

Based on the results of the environmental impacts assessment in Chapter 6, section 7.3.1.1 discusses the main contributors to the environmental impacts of C&D waste cross-regional mobility in Australia. Section 7.3.1.2 then discusses how different scenario settings will affect the environmental impacts of C&D waste management.

7.3.1.1 Environmental impacts contribution analysis

As presented in section 6.2 in Chapter 6, scenario 0.0 considered the life cycle stages of C&D waste including waste collection and onsite sorting, transportation, waste pre-processing, recycling, energy recovery and landfilling, where the environmental impacts for 1 t of C&D waste were mainly negative in value. This is mainly because recycling rates of critical waste materials such as masonry waste and metals are relatively high in the scenario. The recycling of these waste components can reduce significant environmental impacts due to the replacement of raw materials with recycled products.

Based on environmental impacts analysis, the main contributors to each environmental indicator for managing 1 t of generated C&D waste have been identified in Table 7.1. For most environmental indicators (EI-1 to EI-11), steel is a critical contributor to environmental impacts. Organics (timber), aluminium, copper, and paper and cardboard are also major contributors to environmental indicators. Besides, landfilling of masonry materials, paper and cardboard and organics dominated the indicator for environmental impacts – land occupation. In other words, C&D waste materials such as plastics, glass and TLR play less significant roles in contributing to environmental impacts (see analysis in Table 7.1).

Table 7.1: Main contributors for environmental indicators

	EI-1	EI-2	EI-3	EI-4	EI-5	EI-6	EI-7	EI-8	EI-9	EI-10	EI-11	EI-12
	GWP 100 years	AP	EP	ODP	ADP elements	ADP fossil	FAETP inf.	HTP inf.	MAETP inf.	POCP	TETP inf.	Land occupation
Recycling (Masonry materials)												
Energy recovery (Masonry materials)												
Landfilling (Masonry materials)												+
Recycling (Steel)	-	-	-	-	-	-	+	-	-	-	+	
Energy recovery (Steel)												
Landfilling (Steel)	+	+		+	+	+	-	+	+	+	-	+
Recycling (Aluminium)					-	-		-	-		-	
Energy recovery (Aluminium)												
Landfilling (Aluminium)							-		+			
Recycling (Copper)					-							
Energy recovery (Copper)												
Landfilling (Copper)					+	+						
Recycling (Organics)		-	-					-		-	-	
Energy recovery (Organics)			-									
Landfilling (Organics)	+	+	+				-	+		+	+	+
Recycling (Paper & cardboard)							+					
Energy recovery (Paper & cardboard)												
Landfilling (Paper & cardboard)	+		+								+	+
Recycling (Plastic)												
Energy recovery (Plastic)												
Landfilling (Plastic)												+

Note: The main contributors contribute 95% of the value for an environmental indicator;
"+" refers to a factor contribute to the positive value of an environmental indicator;
"-" refers to a factor contribute to the negative value of an environmental indicator.

To be specific:

For the indicator GWP 100 years, it can be found that the recycling of steel contributed to most of the negative value of the impact due to environmental impacts deduction of recycling steel. On the other hand, the landfilling of organics (timber) contributed to most environmental impacts regarding GWP 100 years. The landfilling of steel and paper & cardboard also contributed a significant amount to GWP 100 years. The main environmental impacts contributors to GWP 100 years are shown in Figure 7.2.

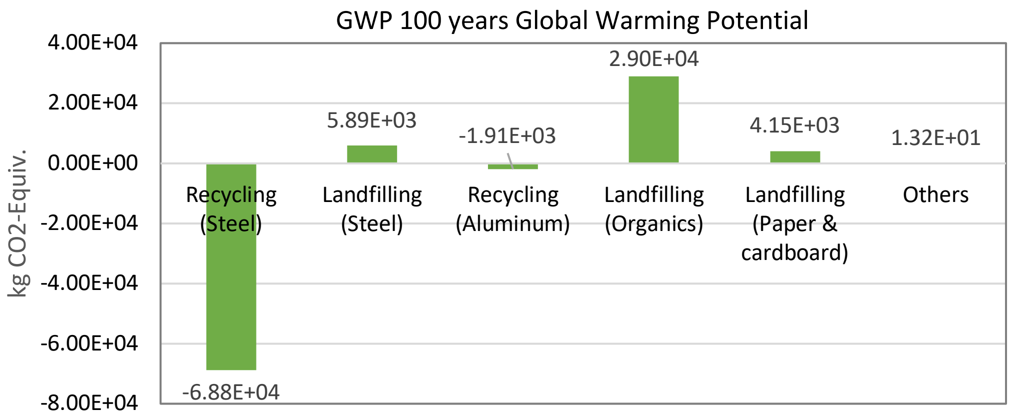


Figure 7.2: Environmental impacts main contributors to GWP 100 years

For the indicator AP, it can be found that the recycling of steel contributed most of the negative value of the impact due to environmental impacts deduction of recycling steel. The recycling of organics and aluminium also contributed to considerable environmental impacts deduction in terms of AP. On the other hand, the landfilling of organics (timber) contributed to most environmental impacts regarding AP. The landfilling of steel also contributes a significant amount of AP. The main environmental impacts contributors to AP are shown in Figure 7.3.

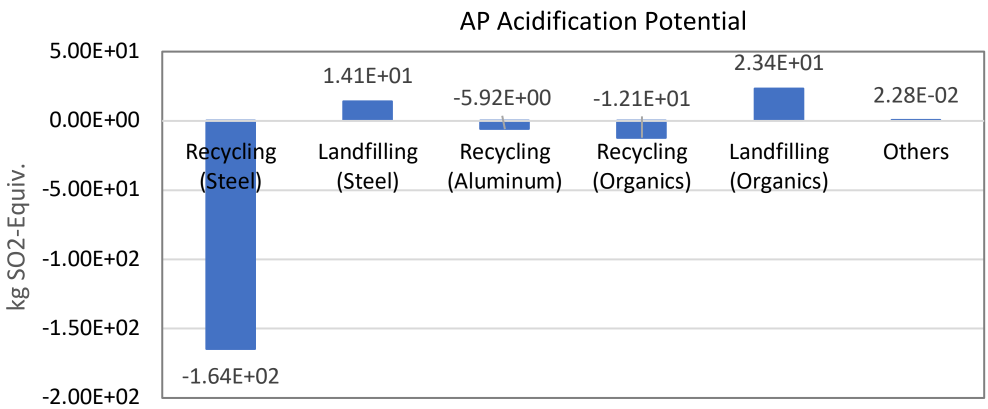


Figure 7.3: Environmental impacts main contributors to AP

For the indicator EP, it can be found that the recycling of steel contributed most of the negative value of the impact due to environmental impacts deduction of recycling steel. The recycling of organics and the energy recovery of timber and aluminium also contribute to considerable environmental impacts deduction in terms of EP. On the other hand, the landfilling of organics (timber) contributed to most environmental impacts regarding EP. The landfilling of paper and cardboard and steel also contributes a significant amount of EP. The main environmental impacts contributors to EP are shown in Figure 7.4.

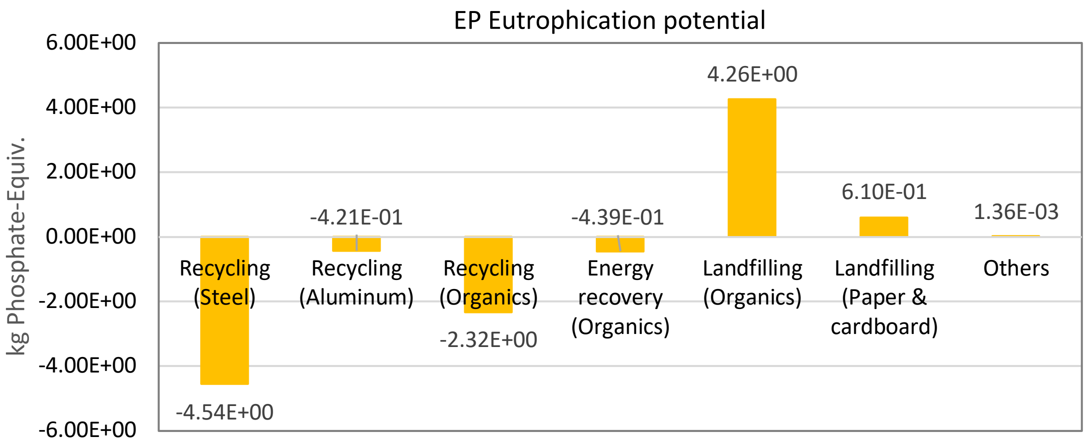


Figure 7.4: Environmental impacts main contributors to EP

For the indicator ODP, it can be found that the landfilling of steel contributed most of the negative value of the impact while the recycling of steel contributed the most environmental impacts regarding ODP. The main environmental impacts contributors to ODP are shown in Figure 7.5.

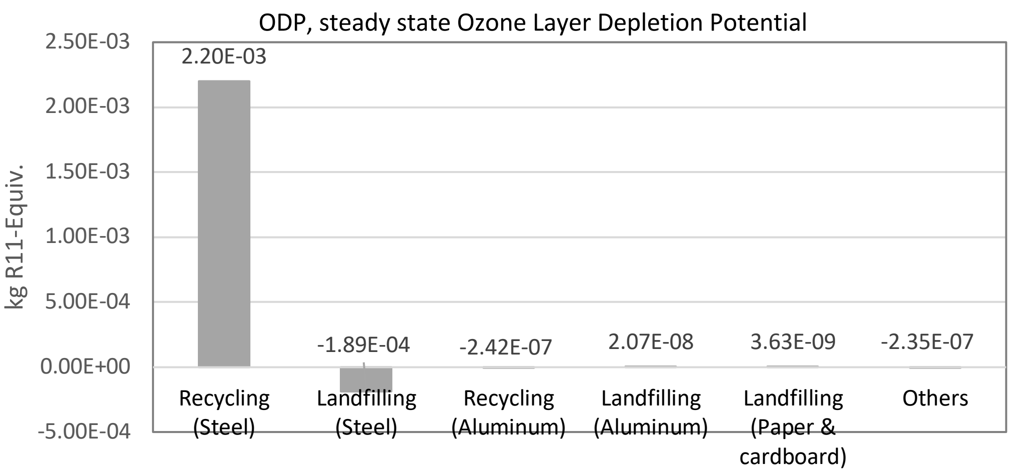


Figure 7.5: Environmental impacts main contributors to ODP

For the indicator ADP elements, it can be found that the recycling of steel contributed most of the negative value of the impact due to the environmental impacts deduction of recycling steel. The recycling of copper also contributes considerable environmental impacts deduction in terms of ADP elements. On the other hand, the landfilling of steel and copper contributed the most environmental impacts regarding ADP. The main environmental impacts contributors to ADP elements are shown in Figure 7.6.

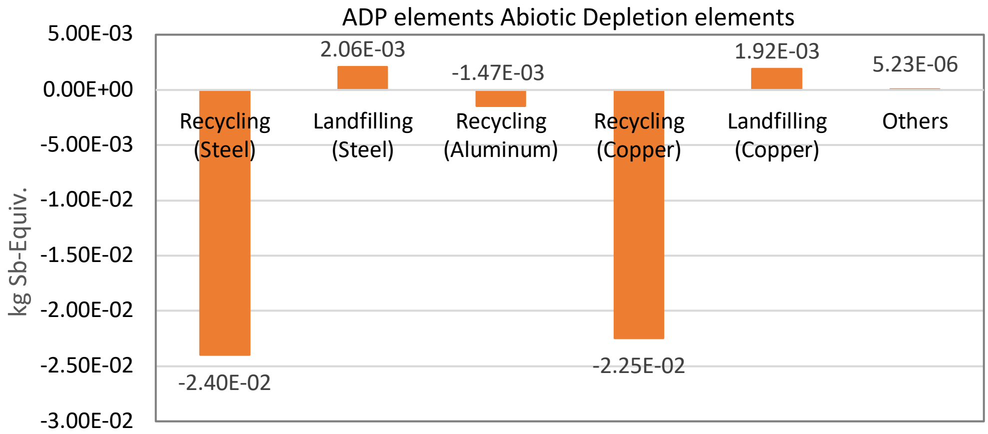


Figure 7.6: Environmental impacts main contributors to ADP elements

For the indicator ADP fossil, it can be found that the recycling of steel contributed most of the negative value due to environmental impacts deduction of recycling steel. The recycling of aluminium also contributes considerable environmental impacts deduction in terms of ADP fossil. On the other hand, the landfilling of steel and organic contributed the most environmental impacts regarding ADP fossil. The main environmental impacts contributors to ADP fossil are shown in Figure 7.7.

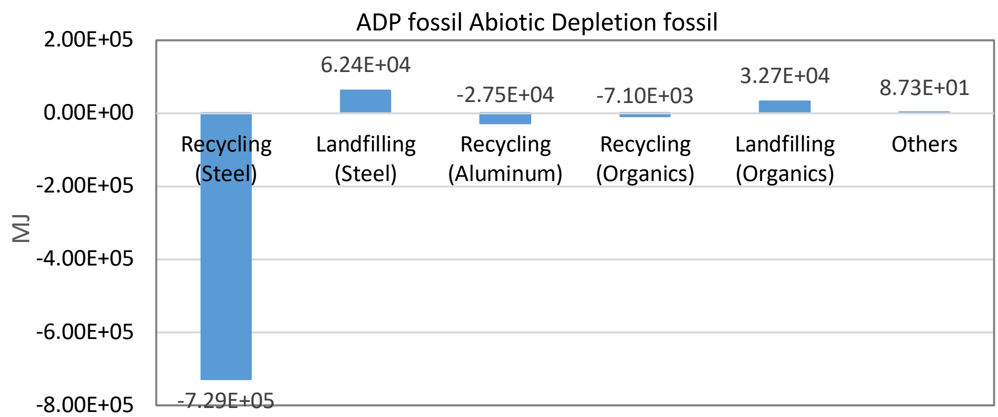


Figure 7.7: Environmental impacts main contributors to ADP fossil

For the indicator FAETP inf., it can be found that the recycling of organics and aluminium contributed significant negative value due to the environmental impacts deduction of recycling steel. On the other hand, the recycling of steel and the landfilling of organics contributed the most environmental impacts regarding FAETP inf. The main environmental impacts contributors to FAETP inf. are shown in Figure 7.8.

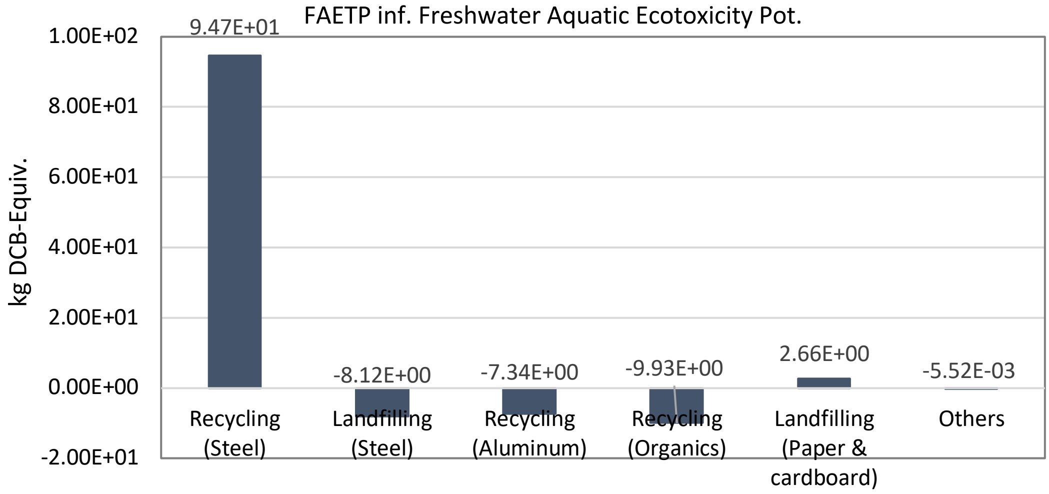


Figure 7.8: Environmental impacts main contributors to FAETP inf.

For the indicator HTP inf., it can be found that the recycling of steel contributed the most significant negative value due to the environmental impacts deduction of recycling steel. The recycling of aluminium and organics contributed significant negative value due to the environmental impacts deduction of recycling. On the other hand, the landfilling of organics and steel contributed the most environmental impacts regarding HTP inf. The main environmental impacts contributions of HTP inf. are shown in Figure 7.9.

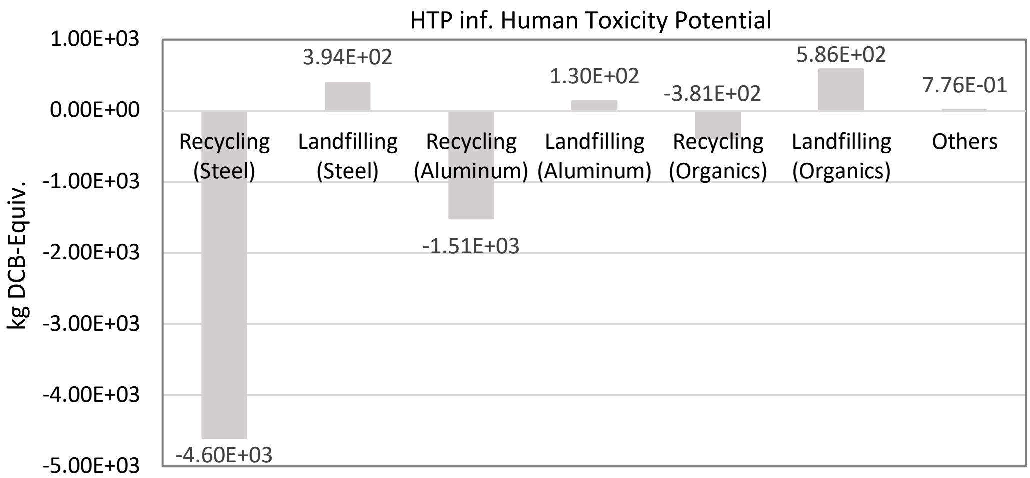


Figure 7.9: Environmental impacts main contributors to HTP inf.

For the indicator MAETP inf., it can be found that the recycling of steel contributed the most significant negative value due to the environmental impacts deduction of recycling steel. The recycling of aluminium also contributed significant negative value due to the environmental impacts deduction of recycling. On the other hand, the landfilling of steel and aluminium contributed the most environmental impacts regarding MAETP inf. The main environmental impacts contributors to MAETP inf. are shown in Figure 7.10.

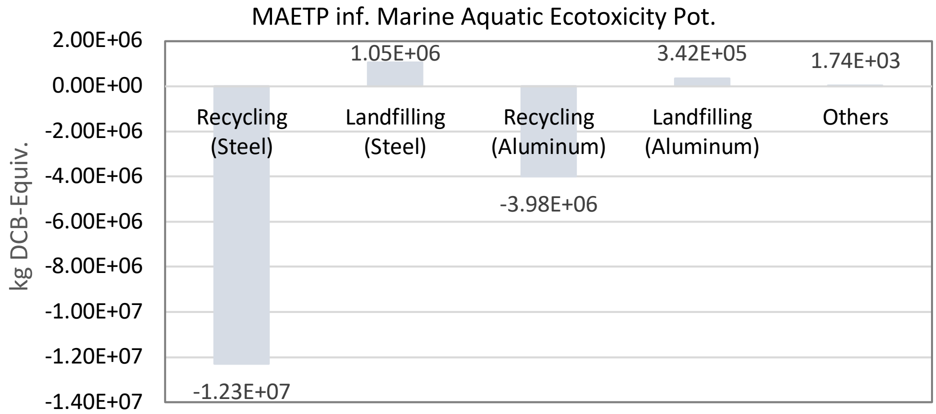


Figure 7.10: Environmental impacts main contributors to MAETP inf.

For the indicator POCP, it can be found that the recycling of steel contributed the most significant negative value due to environmental impacts deduction of recycling steel. On the other hand, the landfilling of organics, steel and paper and cardboard contributed the most environmental impacts regarding POCP. The main environmental impacts contributions of POCP are shown in Figure 7.11.

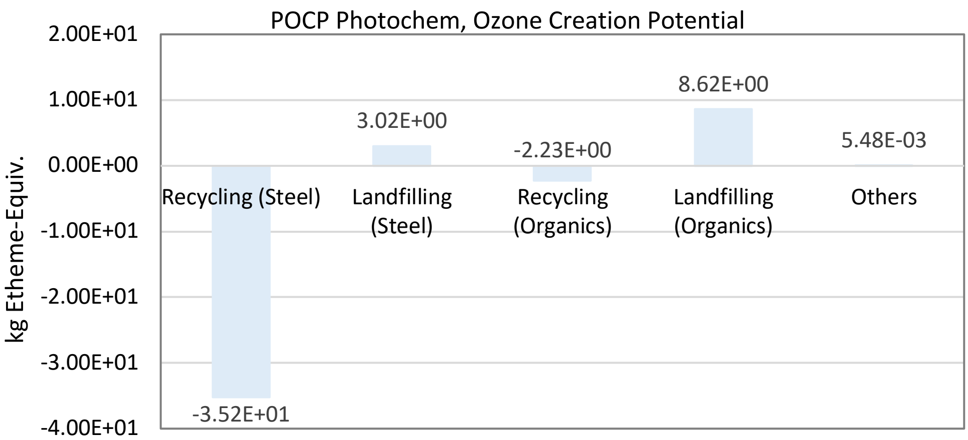


Figure 7.11: Environmental impacts main contributors to POCP

For the indicator TETP inf., it can be found that the recycling of organics contributed the most significant negative value due to environmental impacts deduction of recycling steel. On the other hand, the recycling of steel, the landfilling of organics and paper and cardboard contributed the most environmental impacts regarding TETP inf. The main environmental impacts contributors to TETP inf. are shown in Figure 7.12.

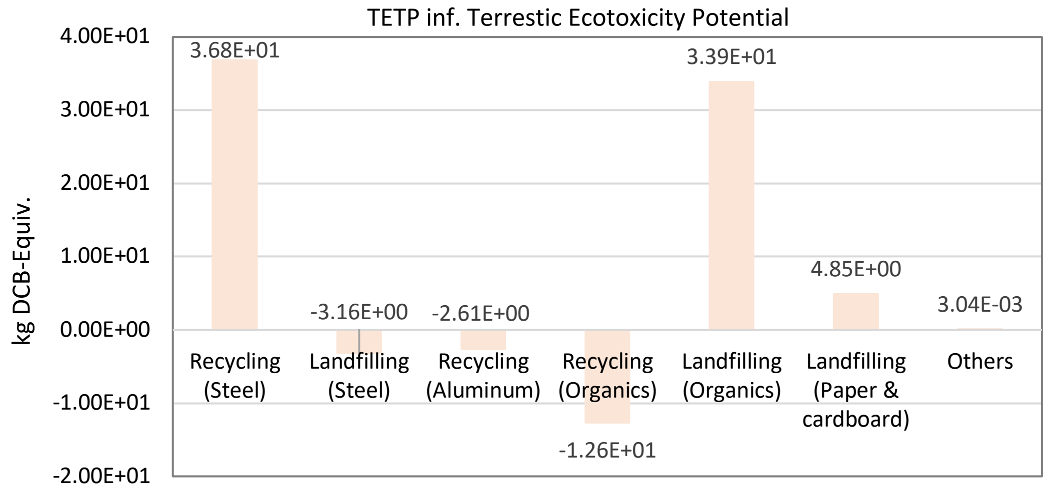


Figure 7.12: Environmental impacts contributors to TETP inf.

For the indicator land occupation, it can be found that the landfilling of masonry materials contributes the most environmental impacts regarding land occupation. The landfilling of paper and cardboard and landfilling of organics also contributed significant environmental impacts regarding land occupation. The main environmental impacts contributors to land occupation are shown in Figure 7.13.

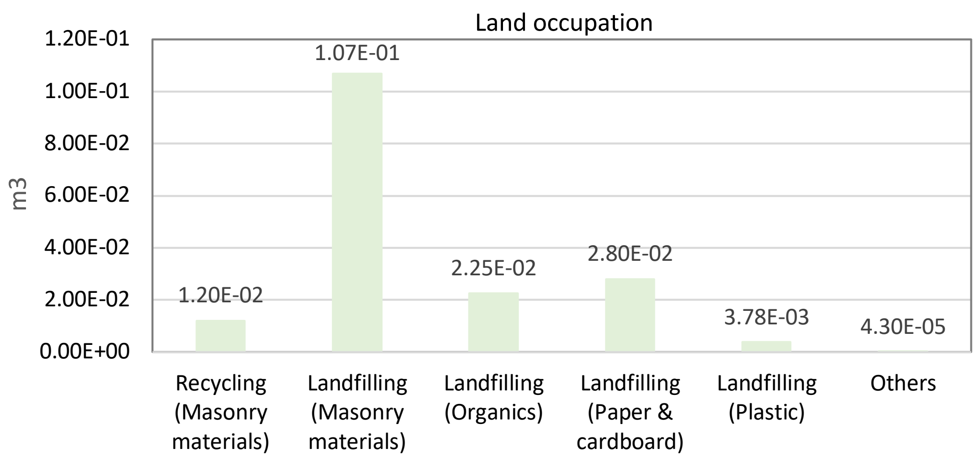


Figure 7.13: Environmental impacts main contributors to land occupation

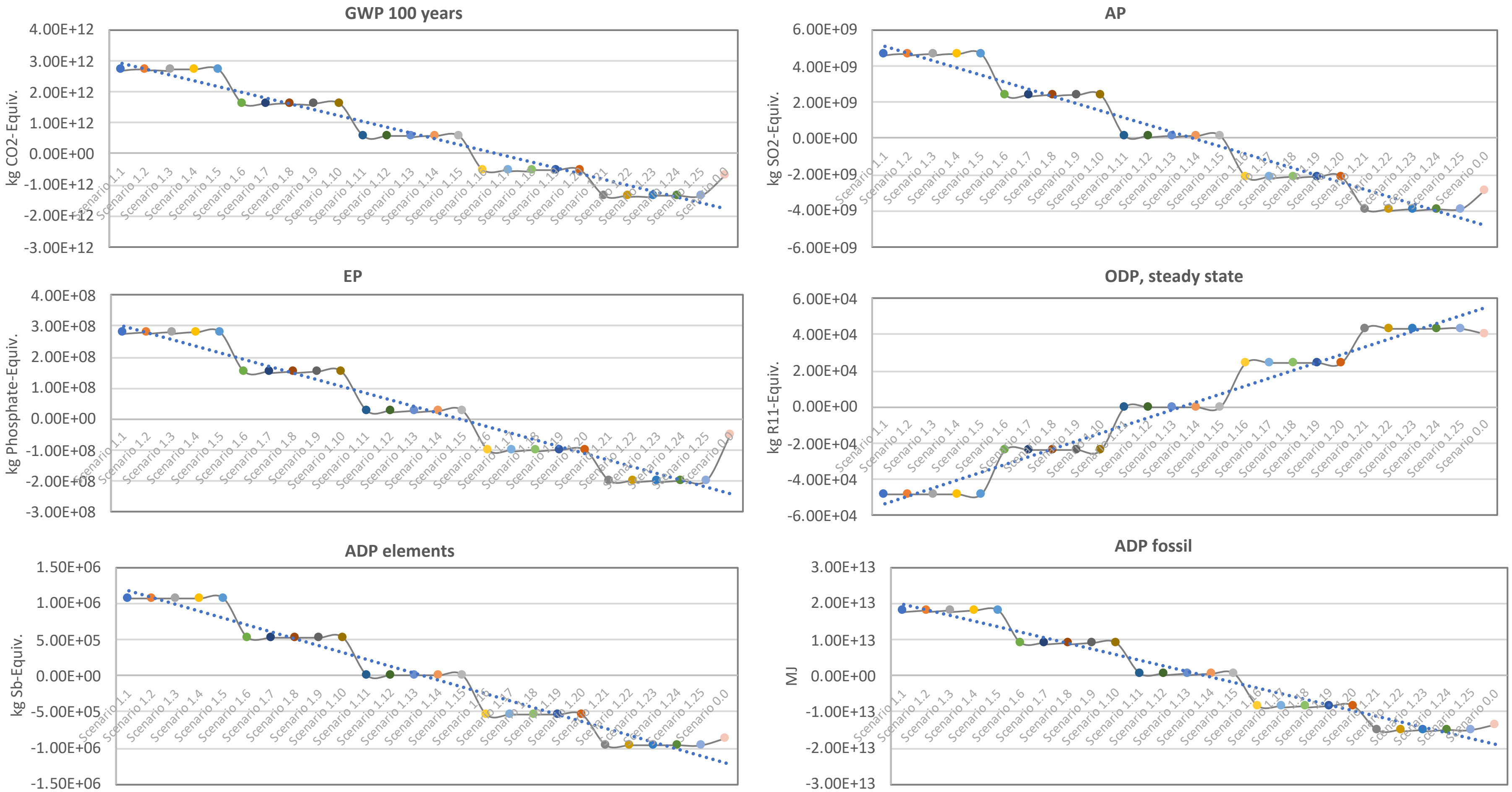
7.3.1.1 Scenario analysis of environmental impacts

Using a quantitative approach, this section conducts the scenario analysis of the environmental impacts for scenario I and scenario II respectively.

- ***Scenario I***

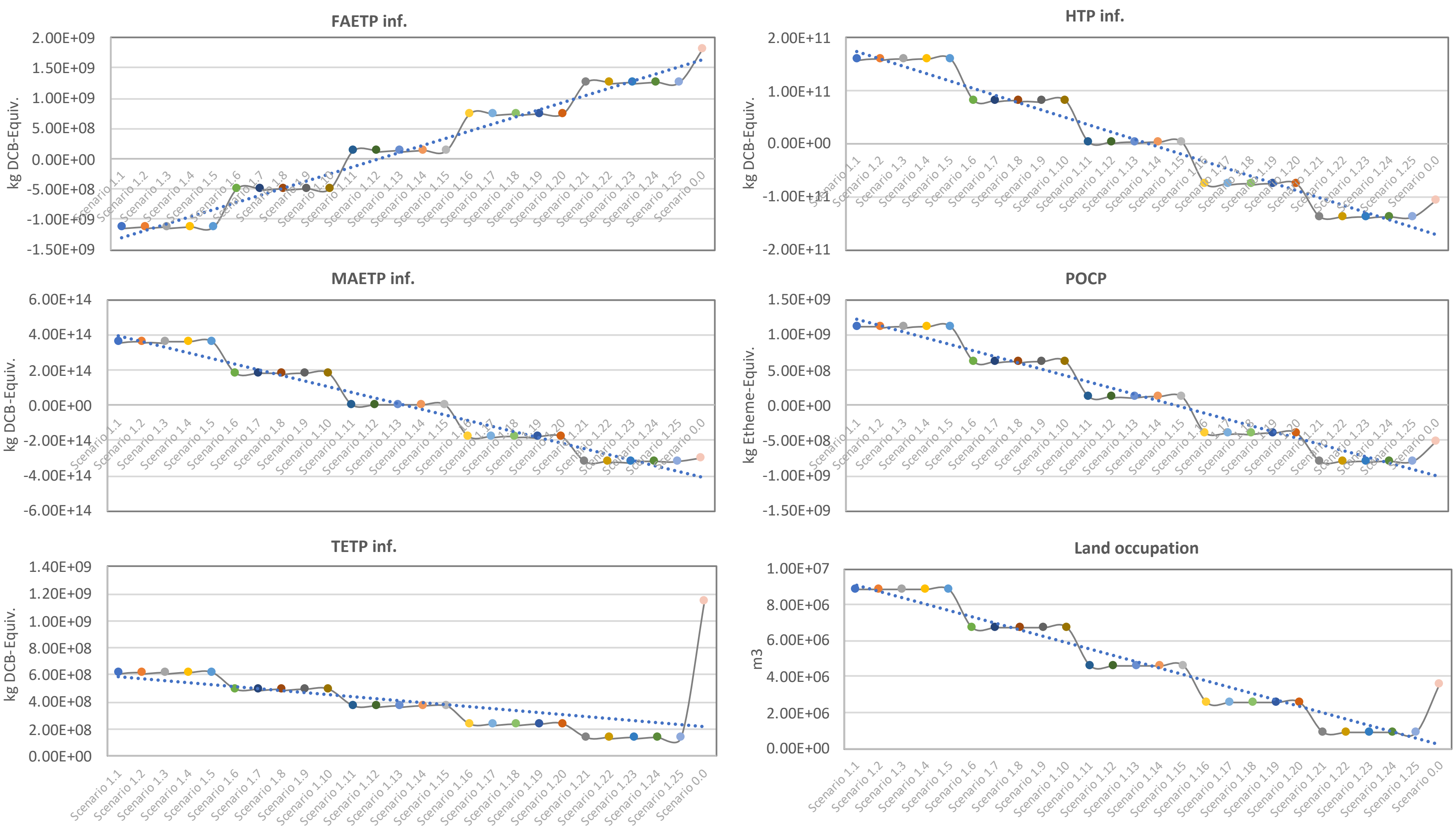
As presented in section 6.2.2 (Chapter 6), scenario setting I for treatment and disposal options will not consider energy recovery but will consider recycling and landfilling (cross-regional mobility +, recycling rate +, landfilling rate -). In scenario setting I, there are 25 scenarios from scenario 1.1 to scenario 1.25 developed by changing the recycling rate and percentage of cross-regional mobility of the waste. For instance, the percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%. The recycling rate will be increased every 25% from 0% to 95%while the landfilling rate will be decreased from 100% to 5% accordingly.

Based on the following analysis, if the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding most environmental indicators. However, if cross-regional mobility can increase the recycling rate, the value of most environmental impact indicators will decrease. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts. The following are analyses for each environmental indicator in scenario I. Scenario analyses of environmental impacts for scenario I are shown in Figure 7.14.



(a)

Figure 7.14: Scenario analyses of environmental impacts (scenario I)



(b)

Figure 7.14 Scenario analyses of environmental impacts (scenario I)

- GWP 100 years

Figure 7.14 (a) compares the environmental impacts regarding GWP 100 years in scenario I. The results show that the GWP 100 years of scenario 1.1 to scenario 1.5 are identical (There are minor differences among these scenarios, but the detailed values cannot be expressed by scientific notation. This situation applies to all indicators below). The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding GWP 100 years. However, if cross-regional mobility can increase the recycling rate, the GWP 100 years will decrease from 2.71E+12 kg CO2 - Equiv. to -1.37E+12 kg CO2 - Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts regarding GWP 100 years. When the recycling rate reaches a certain level (about 63%), GWP 100 years will result in a negative value.

- AP

Figure 7.14(a) compares the environmental impacts regarding AP in scenario I. The situation is similar to GWP, in that the results show that the AP of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding AP. However, if cross-regional mobility can increase the recycling rate, the AP will decrease from 4.68E+09 kg SO2 - Equiv. to -3.89E+09 kg SO2 - Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of the waste, cross-regional mobility can reduce environmental impacts regarding AP. When the recycling rate reaches a certain level (about 50%), the AP will result in a negative value.

- EP

Figure 7.14(a) compares the environmental impacts regarding EP in scenario I. The situation is similar to GWP, in that the results show that the EP of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding EP. However, if cross-regional mobility can increase the recycling rate, the EP will decrease from 2.80E+08 kg Phosphate-Equiv. to -1.99E+08 kg

Phosphate-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts regarding EP. When the recycling rate reaches a certain level (about 55%), the EP will result in a negative value.

- ODP

Figure 7.14(a) compares the environmental impacts regarding ODP in scenario I. The results show that the ODP of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding ODP. The situation is opposite to the above indicators. If cross-regional mobility can increase the recycling rate, the ODP will increase from -4.82E+04 kg R11-Equiv. to 4.434E+04 kg R11-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility will decrease environmental impacts regarding ODP. When the recycling rate reaches a certain level (about 50%), the ODP will result in a positive value.

- ADP elements

Figure 7.14(a) compares environmental impacts regarding ADP elements in scenario I. The situation is similar to GWP, in that the results show that ADP elements of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding ADP elements. However, if cross-regional mobility can increase the recycling rate, the value of ADP elements will decrease from 1.07E+06 kg Sb-Equiv. to -9.67E+05 kg Sb-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts regarding ADP elements. When the recycling rate reaches a certain level (about 50%), ADP elements will result in a negative value.

- ADP fossil

Figure 7.14(a) compares environmental impacts regarding ADP fossil in scenario I. The situation is similar to ADP elements, in that the results show that the ADP fossil of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20 and scenario 1.21 to scenario

1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding ADP fossil. However, if cross-regional mobility can increase the recycling rate, the value of ADP elements will decrease from 1.79E+13 MJ to -1.52E+13 MJ. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts regarding ADP fossil. When the recycling rate reaches a certain level (about 50%), ADP fossil will result in a negative value.

- FAETP inf.

Figure 7.14(b) compares environmental impacts regarding FAETP inf. in scenario I. The results show that the FAETP inf. of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding FAETP inf. The situation is opposite to ADP fossil. If cross-regional mobility can increase the recycling rate, the FAETP inf. will increase from -1.13E+09 kg DCB-Equiv. to 1.26E+09 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of the waste, cross-regional mobility will decrease the environmental impacts regarding FAETP inf. When the recycling rate reaches a certain level (about 45%), the ODP will result in a positive value.

It is noted that the results of FAETP inf. of scenario 0.0 are higher than all other scenarios due to multiple factors. When the original data is checked, it is found there are two main reasons. Firstly, the recycling rates are set the same for all C&D waste materials in scenario 1.1 to scenario 1.25 while the recycling rates of waste materials of scenario 0.0 are set based on the current situation and therefore the rates are dramatically different (Figure 4.15 in Chapter 4); secondly, the results of FAETP inf. of scenario 0.0 are mainly affected by recycling steel, landfilling steel, recycling aluminium, recycling organics and landfilling organics. For instance, the recycling rates of steel and aluminium in scenario 0.0 are similar to the recycling rates in scenario 1.25. However, the recycling rate of organics in scenario 0.0 is about 55% and the recycling rate of the materials in scenario 1.25 is 95%. If all these factors are combined, the results of FAETP inf. of scenario 0.0 are higher than other scenarios.

- HTP inf.

Figure 7.14(b) compares environmental impacts regarding HTP inf. in scenario I. The situation is similar to ADP elements, in that the results show that the HTP inf. of scenario 1.1 to scenario 1.5 are identical. The situation is similar to those happening in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding HTP inf. However, if cross-regional mobility can increase the recycling rate, the value of HTP inf. will decrease from 1.59E+11 kg DCB-Equiv. to –1.39e+11 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce the environmental impacts regarding HTP inf. When the recycling rate reaches a certain level (about 50%), HTP inf. will result in a negative value.

- MAETP inf.

Figure 7.14(b) compares environmental impacts regarding MAETP inf. in scenario I. The situation is similar to HTP inf. in that the results show that MAETP inf. of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding MAETP inf. However, if cross-regional mobility can increase the recycling rate, the value of MAETP inf. will decrease from 3.57E+14 kg DCB-Equiv. to –3.22E+14 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts regarding MAETP inf. When the recycling rate reaches a certain level (about 50%), MAETP inf. will result in a negative value.

- POCP

Figure 7.14(b) compares environmental impacts regarding POCP in scenario I. The situation is similar to HTP inf. in that the results show that the POCP of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding POCP. However, if cross-regional mobility can increase the recycling rate, the value of MAETP inf. will decrease from 1.12E+09 kg Etheme-Equiv. to –7.89E+08 kg Etheme-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of the waste, cross-regional mobility can reduce environmental impacts regarding POCP. When the recycling rate reaches a certain level (about 55%), POCP will result in a negative value.

- TETP inf.

Figure 7.14(b) compares environmental impacts regarding TETP inf. in scenario I. The situation is similar to HTP inf. in that the results show that the TETP inf. of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding TETP inf. However, if cross-regional mobility can increase the recycling rate, the value of TETP inf. will decrease from 6.24E+08 kg DCB-Equiv. to 1.37E+08 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts regarding TETP inf.

Similar to FAETP inf., the results of TETP inf. of scenario 0.0 are higher than all other scenarios due to multiple factors. When the original data is checked, it is found there are two main reasons. Firstly, recycling rates are set the same for all C&D waste materials in scenario 1.1 to scenario 1.25 while recycling rates of waste materials of scenario 0.0 are set based on the current situation and the rates are dramatically different; secondly, the results of TETP inf. of scenario 0.0 are mainly affected by recycling steel, landfilling steel, recycling aluminium, recycling organics and landfilling organics. For instance, the recycling rates of steel and aluminium in scenario 0.0 are similar to recycling rates in scenario 1.25; however, recycling rates of organics in scenario 0.0 is about 55% and recycling rates of material in scenario 1.25 is 95%. If all these factors are combined, the results of TETP inf. of scenario 0.0 are higher than other scenarios.

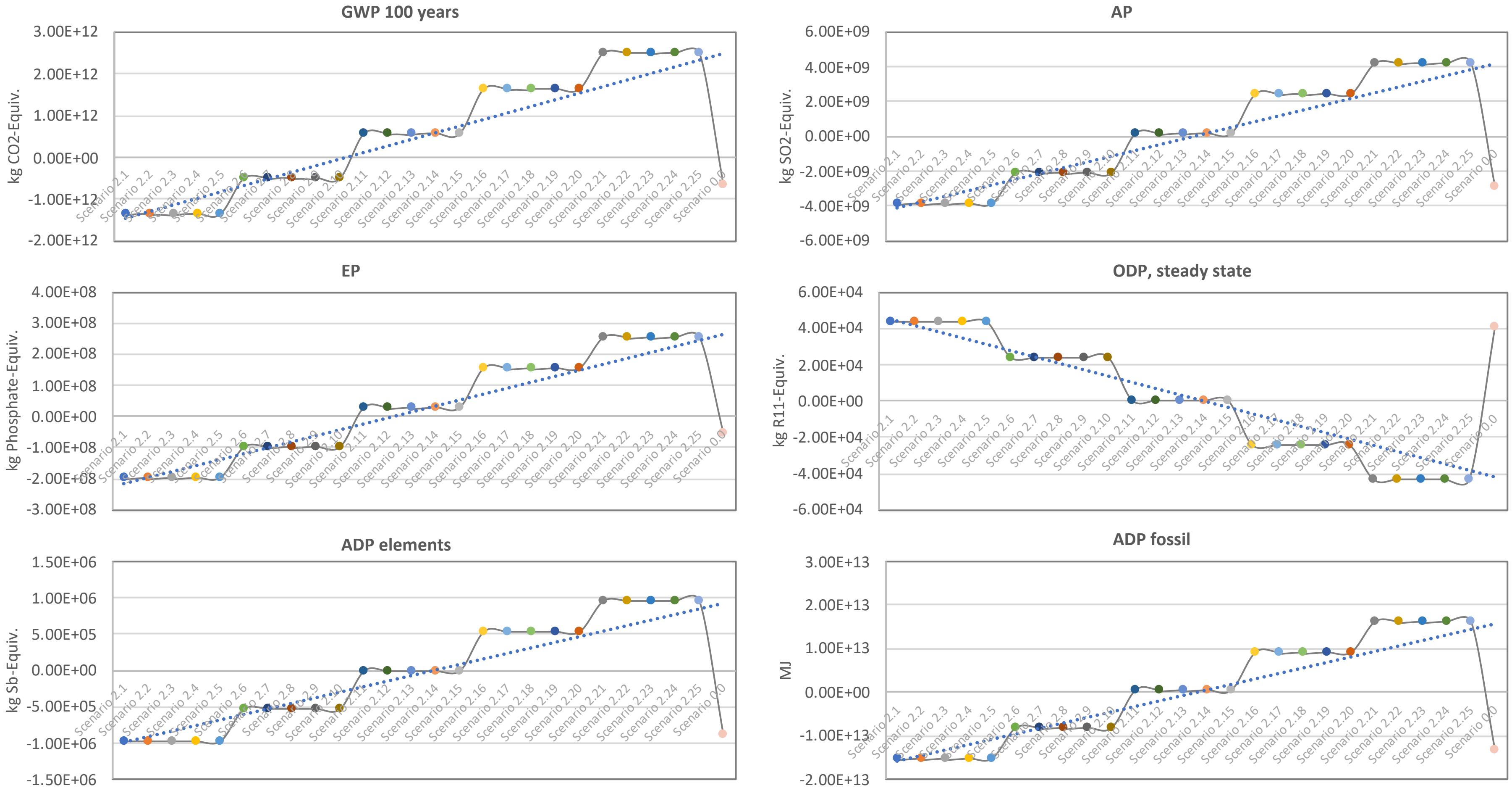
- Land occupation

Figure 7.14(b) compares environmental impacts regarding land occupation in scenario I. The results show that land occupation of scenario 1.1 to scenario 1.5 are identical. The situation is similar in scenario 1.6 to scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding land occupation. However, if cross-regional mobility can increase the recycling rate, the value of land occupation will decrease from 8.81E+06 m^3 to 8.59E+05 m3. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts regarding land occupation.

- ***Scenario II***

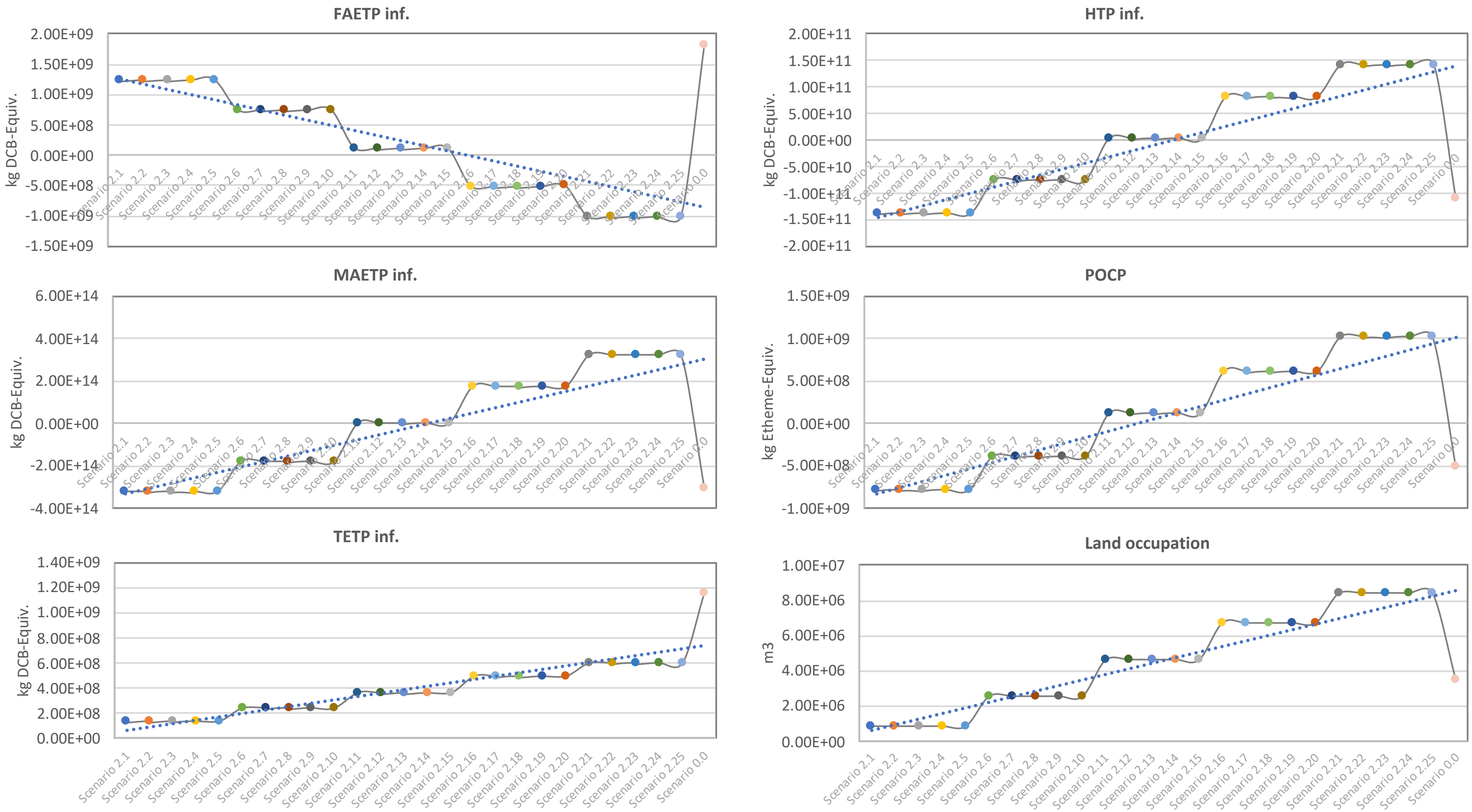
As presented in section 6.2.3 (Chapter 6), scenario setting II for the treatment and disposal options will not consider energy recovery but will consider recycling and landfilling (cross-regional mobility +, recycling rate -, landfilling rate +). In the scenario setting II, there are 25 scenarios from scenario 2.1 to scenario 2.25, developed by changing the recycling rate and the percentage of cross-regional mobility of waste. For instance, the percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%. The recycling rate will be decreased every 25% from 95% to 0% while the landfilling rate will be increased from 5% to 100% accordingly.

Based on the analysis, if the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding most environmental indicators. However, if cross-regional mobility can increase the landfilling rate, environmental impacts will increase. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts. Detailed analysis for each environmental indicator in scenario II and analysis of environmental impacts for scenario II are shown in Figure 7.15.



(a)

Figure 7.15: Scenario analysis of environmental impacts (scenario II)



(b)

Figure 7.15 Scenario analysis of environmental impacts (scenario II)

- GWP 100 years

Figure 7.15(a) compares environmental impacts regarding GWP 100 years in scenario II. The results show that the GWP 100 years of scenario 2.1 to scenario 2.5 are identical (There are minor difference among scenarios if the original data is checked). The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding GWP 100 years. However, if cross-regional mobility can increase the landfilling rate, the GWP 100 years will increase from – 1.37E+12 kg CO2 - Equiv. to 2.49E+12 kg CO2 - Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding GWP 100 years.

- AP

Figure 7.15(a) compares environmental impacts regarding AP in scenario II. Similar to GWP, the results show that the AP of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding AP. However, if cross-regional mobility increases the landfilling rate, the AP will increase from -3.89E+09 kg SO2 - Equiv. to 4.23E+09 kg SO2 - Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding AP.

- EP

Figure 7.15(a) compares environmental impacts regarding EP in scenario II. Similar to GWP, the results show that the EP of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding EP. However, if cross-regional mobility increases the landfilling rate, the EP will increase from -1.99E+08 kg Phosphate-Equiv. to 2.54E+08 kg Phosphate-Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding EP.

- ODP

Figure 7.15(a) compares environmental impacts regarding ODP in scenario II. The results show that the ODP of scenario 2.1 to scenario 2.5 are identical. This is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding ODP. The situation is opposite to the above indicators. If cross-regional mobility increases the landfilling rate, the ODP will decrease from 4.34E+04 kg R11-Equiv. to -4.34E+04 kg R11-Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding ODP.

- ADP elements

Figure 7.15(a) compares environmental impacts regarding ADP elements in scenario II. The situation is similar to GWP, the results show that ADP elements of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding ADP elements. However, if cross-regional mobility increases the landfilling rate, the value of ADP elements will increase from -9.67E+05 kg Sb-Equiv. to 9.64E+05 kg Sb-Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding ADP elements.

- ADP fossil

Figure 7.15(a) compares environmental impacts regarding ADP fossil in scenario II. The situation is similar to ADP elements, in that the results show that the ADP fossil of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding ADP fossil. However, if cross-regional mobility increases the landfilling rate, the value of ADP elements will increase from -1.52E+13 MJ to 1.62E+13 MJ. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding ADP fossil.

- FAETP inf.

Figure 7.15(b) compares environmental impacts regarding FAETP inf. in scenario II. The results show that the FAETP inf. of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding FAETP inf. The situation is opposite to ADP fossil. If cross-regional mobility increases the landfilling rate, the FAETP inf. will increase from 1.26E+09 kg DCB-Equiv. to -1.01E+09 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding FAETP inf.

- HTP inf.

Figure 7.15(b) compares environmental impacts regarding HTP inf. in Scenario II. The situation is similar to ADP elements in that the results show that HTP inf. of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding HTP inf. However, if cross-regional mobility increases the landfilling rate, the value of HTP inf. will decrease from 1.39E+11 kg DCB-Equiv. to 1.43E+11 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding HTP inf.

- MAETP inf.

Figure 7.15(b) compares environmental impacts regarding MAETP inf. in scenario II. The situation is similar to HTP inf. in that the results show that MAETP inf. of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding MAETP inf. However, if cross-regional mobility increases the landfilling rate, the value of MAETP inf. will increase from 3.22E+14 kg DCB-Equiv. to 3.22E+14 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding MAETP inf.

- POCP

Figure 7.15(b) compares environmental impacts regarding POCP in scenario II. The situation is similar to HTP inf. in that the results show that POCP of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding POCP. However, if cross-regional mobility can increase the recycling rate, the value of MAETP inf. will decrease from -7.89E+08 kg Etheme-Equiv. to 1.02E+09 kg Etheme-Equiv. In other words, if cross-regional mobility of C&D waste increases the recycling rate of waste, cross-regional mobility will increase environmental impacts regarding POCP.

- TETP inf.

Figure 7.15(b) compares environmental impacts regarding TETP inf. in scenario II. The situation is similar to HTP inf. in that the results show that TETP inf. of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding TETP inf. However, if cross-regional mobility increases the landfilling rate, the value of TETP inf. will increase from 1.36E+08 kg DCB-Equiv. to 5.98E+08 kg DCB-Equiv. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility can reduce the environmental impacts regarding TETP inf.

- Land occupation

Figure 7.15(b) compares environmental impacts regarding land occupation in scenario II. The results show that land occupation of scenario 2.1 to scenario 2.5 are identical. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect environmental impacts regarding land occupation. However, if cross-regional mobility increases the recycling rate, the value of land occupation will increase from 8.59E+05 m^3 to 8.39E+06 m3. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts regarding land occupation.

7.3.2 Economic impacts of C&D waste cross-regional mobility in Australia

7.3.2.1 Economic impacts contribution analysis

As presented in section 6.3.1 (Chapter 6) in scenario 0.0, considering life cycle stages of C&D waste including waste collection and onsite sorting, transportation, waste pre-processing, recycling, energy recovery and landfilling, the industry income for generated C&D waste is $6.95 billion. Based on this analysis, waste collection, transportation and pre-processing contribute 52.1% of industry income. This is followed by recycling of masonry waste (19.7%), recycling of metals (13%), landfilling of masonry waste (7.4%), recycling of other unclassified waste (5%), and recycling of timber (1.1%). The contribution from other factors is minor (less than 2%). Economic impacts and their contribution are shown in Figure 7.16. The data in Figure 7.16 can be found in Table A-7.2 in Appendix B.

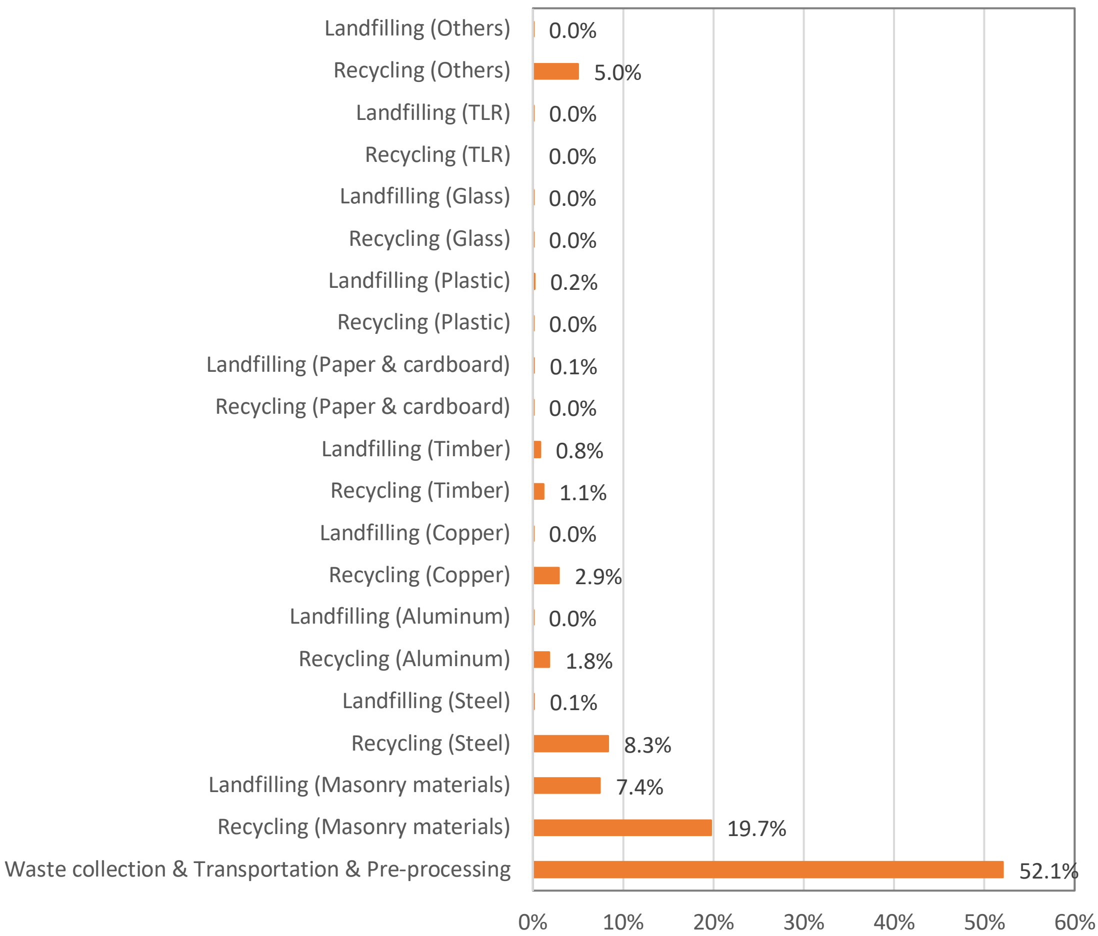


Figure 7.16: Economic impacts contribution analysis

7.3.2.2 Scenario analysis of economic impacts

Scenario I

As presented in section 6.3.2, scenario setting I for treatment and disposal options will not consider energy recovery but will consider recycling and landfilling (cross-regional mobility +, recycling rate +, landfilling rate -). In scenario setting I, there are 25 scenarios from scenario 1.1 to scenario 1.25, developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, the percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%. The recycling rate will be increased every 25% from 0% to 95% while the landfilling rate will be decreased from 100% to 5% accordingly.

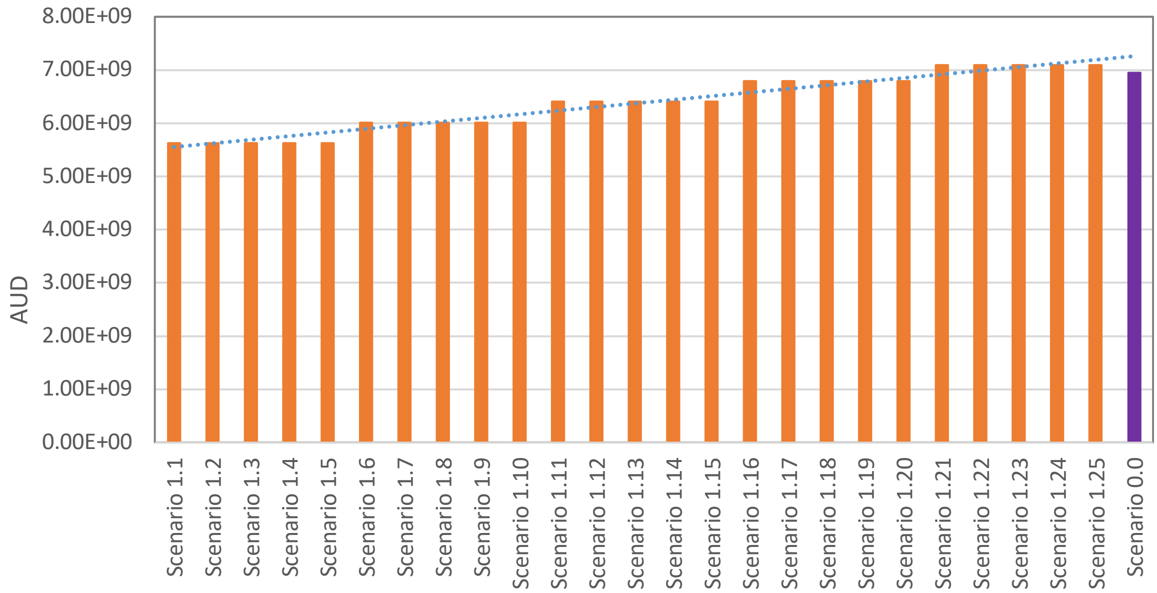


Figure 7.17: Scenario analysis of economic impacts (scenario I)

Figure 7.17 compares the economic impact in AUD in terms of industry income in scenario I. The results show that industry income of scenario 1.1 to scenario 1.5 are identical. There are minor differences among scenarios if the original data is checked. The situation is similar in scenario 1.6 to Scenario 1.10, scenario 1.11 to scenario 1.15, scenario 1.16 to scenario 1.20, and scenario 1.21 to scenario 1.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect economic performance. However, if cross-regional mobility can increase the recycling rate, industry income will increase from 5.63 billion AUD to 7.10 billion AUD. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility activity can increase industry income.

The industry income in the current situation (scenario 0.0) has reached a relatively high level to the value of 6.95 billion AUD. This is because industry income was mainly generated from waste collection and transportation and pre-processing, recycling of masonry waste, recycling of metals, and recycling of other unclassified waste. Thus, the management rate, recycling rate of masonry materials (69.2%), recycling of metals (92.1%), and other unclassified waste (97.7%) are relatively high. Detailed results of scenario analysis of economic impacts for scenario I are shown in Figure 7.18 and Table A-7.3 in Appendix B.

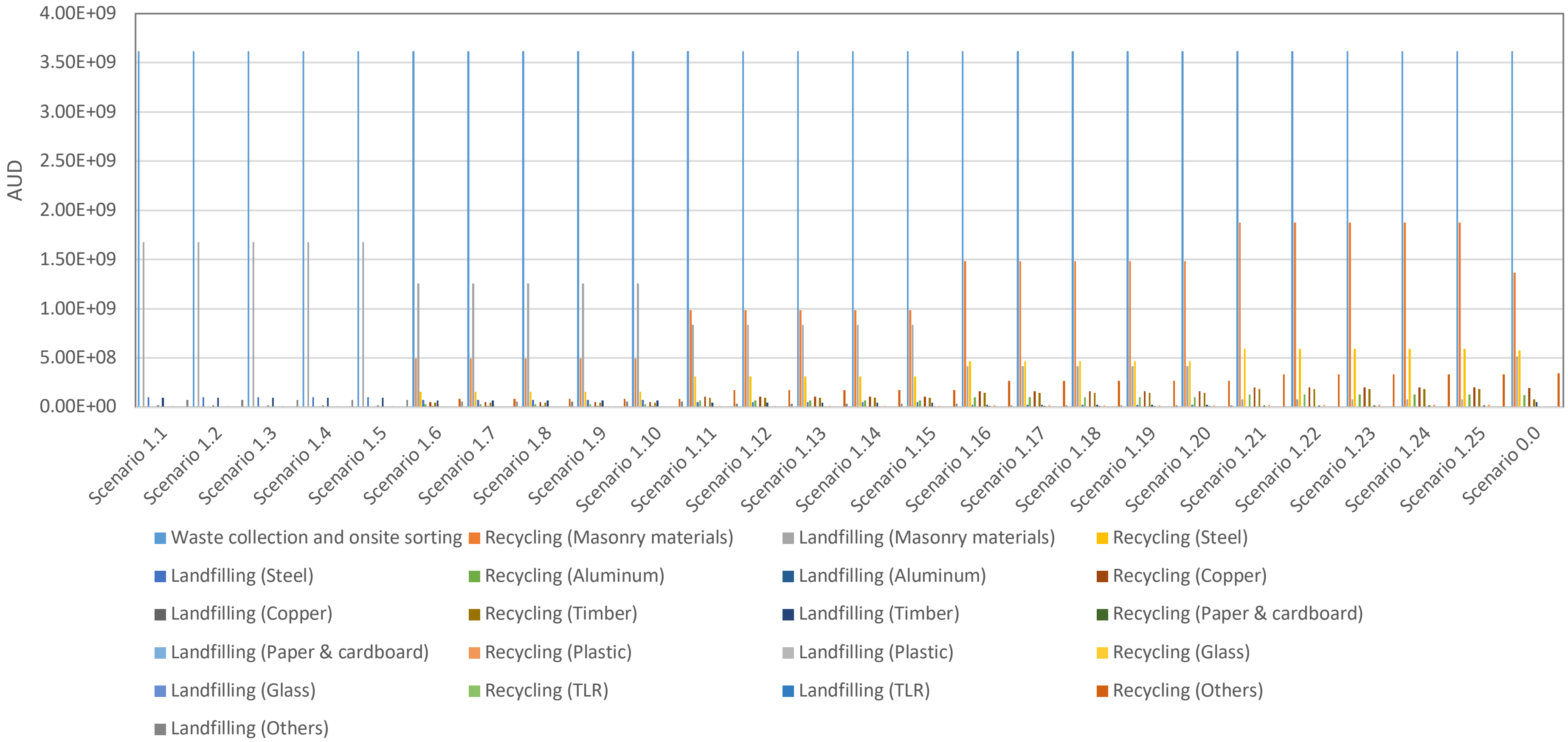


Figure 7.18: Scenario analysis of economic impacts for scenario I

Scenario II

As presented in section 6.3.3, scenario setting II for treatment and disposal options will not consider energy recovery but will consider recycling and landfilling (cross-regional mobility +, recycling rate -, landfilling rate +). In scenario setting II, there are 25 scenarios from scenario 2.1 to scenario 2.25, developed by changing the recycling rate and percentage of cross-regional mobility of waste. For instance, the percentage of cross-regional mobility of waste will be allocated from 0% to 100% by every 25%. The recycling rate will be decreased every 25% from 95% to 0%while the landfilling rate will be increased from 5% to 100% accordingly.

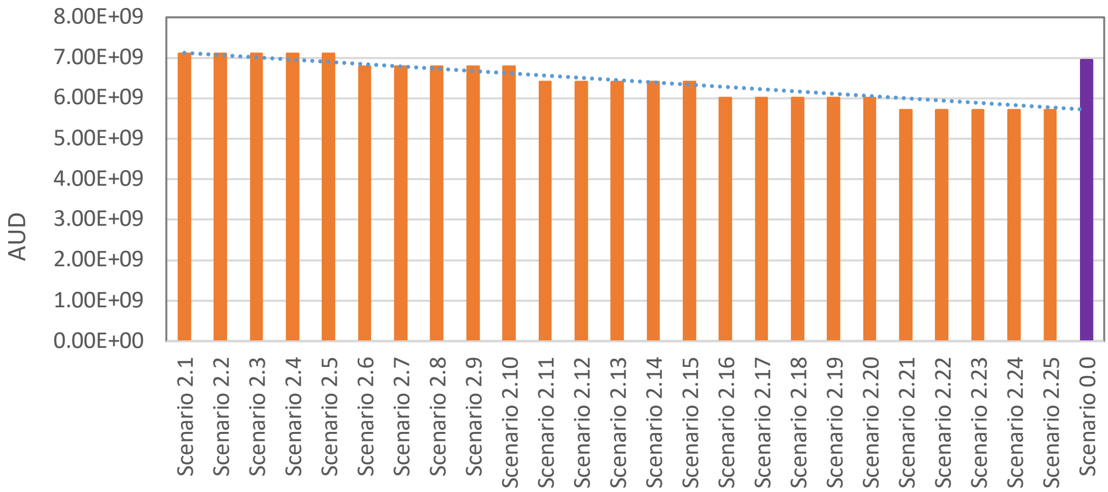


Figure 7.19: Scenario analysis of economic impacts (scenario II)

Figure 7.19 compares the economic impact in terms of industry income in scenario II. The results show that industry income of scenario 2.1 to scenario 2.5 are identical. There are minor differences among scenarios if original data is checked. The situation is similar in scenario 2.6 to scenario 2.10, scenario 2.11 to scenario 2.15, scenario 2.16 to scenario 2.20, and scenario 2.21 to scenario 2.25. If the recycling rate and landfilling rate are fixed, cross-regional mobility will not significantly affect economic performance. However, if cross-regional mobility increases the landfilling rate, industry income will decrease from 7.10 billion AUD to 5.63 billion AUD. In other words, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility activity will decrease industry income. Detailed results of scenario analysis of economic impacts for scenario I are shown in Figure 7.20 and Table A-7.4 in Appendix B.

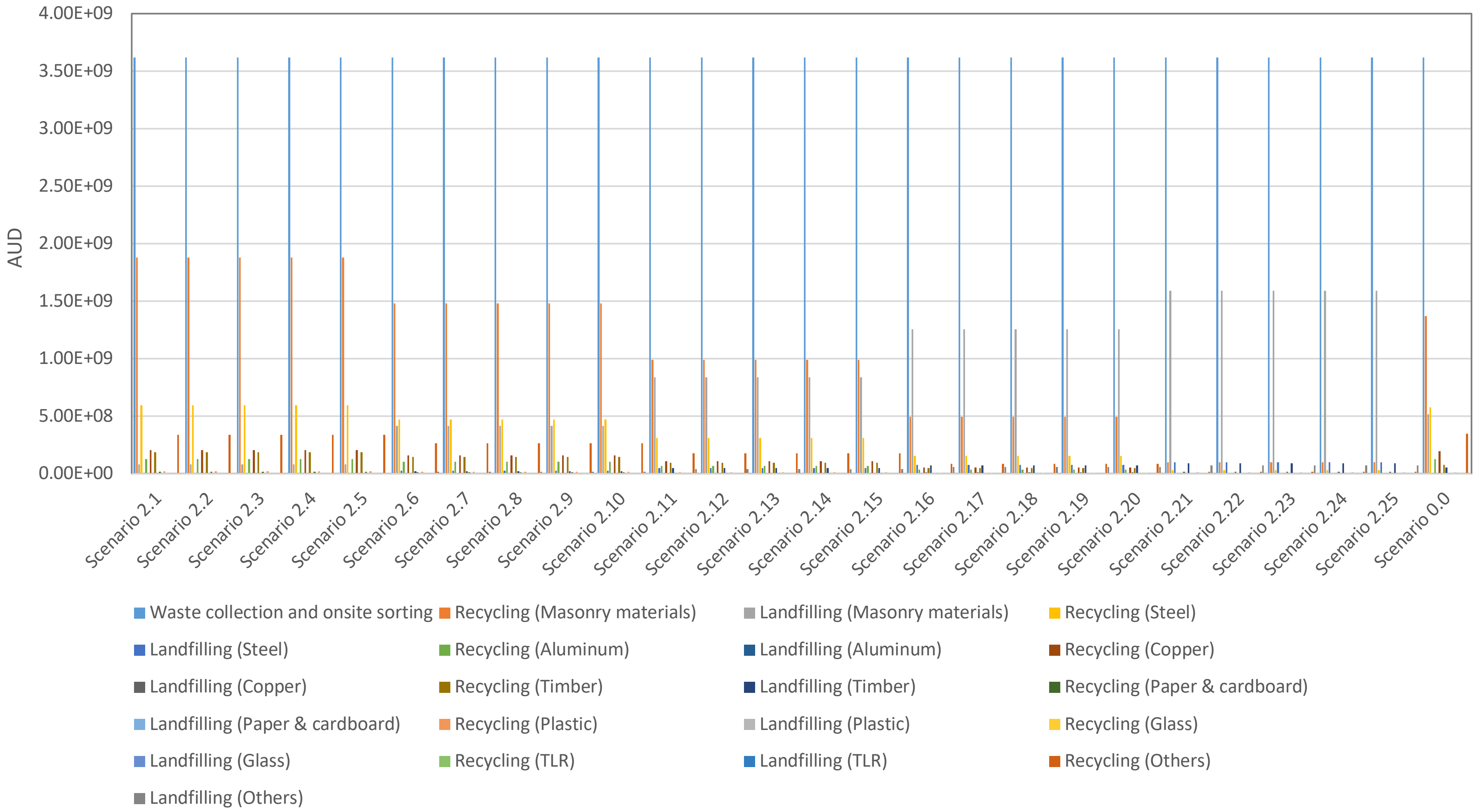


Figure 7.20: Scenario analysis of economic impacts for Scenario II (detailed)

7.3.3 Social impacts of C&D waste cross-regional mobility in Australia

As cross-regional mobility of C&D waste affects the amount of waste being managed in regions where waste originally generated and regions where waste was imported, social impacts regarding employment are affected by the cross-regional issue. For instance, if a significant amount of C&D waste generated in NSW was transported to QLD for further treatment or to landfill, the amount of C&D waste treated in NSW will decrease while the amount of C&D waste treated in QLD will increase. As a result, employment for C&D waste management will increase in QLD for managing the increasing C&D waste originally generated in NSW. At the same time, the demand for employment for managing C&D waste in NSW will decrease.

Based on the results in section 6.4, it is found that because of cross-regional mobility of C&D waste, ACT, VIC and QLD have gained 328.17 p, 12.19 p, and 305.71 p full-time equivalent respectively, while NSW, SA and WA have lost 958.11 p, 29.09 p and 4.88 p full-time equivalent respectively. Similarly, if a significant amount of C&D waste generated in Australia is transported for further processing in other countries, employment for the management of C&D waste in Australia will decrease.

The indicator used for the evaluation of social impacts of C&D waste cross-regional mobility in Australia is the employment of people (full-time equivalent), based on the whole C&D waste management industry in Australia. This includes all employment involving the life cycle of C&D waste management from waste collection, transportation, pre-processing, recycling and final disposal. Due to the limitation of data, it was not possible to conduct scenario analyses to examine how cross-regional mobility of C&D waste would affect social impacts, considering different treatment methods based on the same approaches adopted in environmental and economic impacts, as discussed in the above sections.

Based on the analysis, if a considerable amount of C&D waste generated involves cross-regional mobility, there will generally be a reduction in employment opportunities for managing waste in the regions that export waste and a consequential increase in employment opportunities for managing C&D waste in regions that import waste.

7.4 Recommended strategies for management of cross-regional mobility of C&D waste

Based on the findings in Chapter 5, Chapter 6 and sections 7.2 and 7.3 in this chapter, ten optimisation strategies are recommended for the management of cross-regional mobility of C&D waste in Australia. There are many stakeholders in C&D waste management, such as federal government, state government, local government, waste generator, waste collector, waste transporter, waste reprocessor, waste recycler, landfill operator, recycled products consumer, industry association and so on. For each recommended optimisation strategy, there are initiators (who initiate the measure), participants (involved in the measure), and subjects (who undertake the measure). For instance, the strategy for managing C&D waste, as a critical sector of waste management in Australia, should be initiated by the federal government, while state governments, local governments and industry associations participate in the development of policies and measures. As a consequence, these policies and measures will affect multiple stakeholders such as waste generators, waste collectors, waste transporter, waste reprocessors, waste recycler and landfill operators. Figure 7.21 presents a framework of recommended optimisation strategies for the management of cross-regional mobility of C&D waste in Australia.

	Recommended optimisation strategies	initiator	Participants	Subjects
RS 1:	Managing C&D waste as a critical sector of waste management in Australia	Federal government	State government Local government Industry association	Waste generator Waste collector Waste transporter Waste reprocessor Waste recycler Landfill operator
RS 2:	Applying an integrated waste management strategy	Local government	Federal government State government Industry association	Waste collector Waste transporter Waste reprocessor Waste recycler Landfill operator
RS 3:	Developing a better recycled products market	Local government	Federal government State government Industry association	Waste generator Waste collector Waste reprocessor Waste recycler Recycled products consumer
RS 4:	Enhancing South Australia as the centre for waste recycling in Australia	State government	Federal government Local government Industry association	Waste transporter Waste reprocessor Waste recycler Landfill operator Recycled products consumer
RS 5:	Enhancing cross- border management of regional landfilling in eastern regions of Australia	State government	Local government Industry association	Waste generator Waste collector Waste transporter Waste reprocessor Landfill operator
RS 6:	Developing appropriate landfill levies for C&D waste	State government	Federal government Local government Industry association Waste reprocessor	Waste generator Landfill operator
RS 7:	Developing better management procedures for certain types of C&D waste such as metals, masonry waste and timber	Industry association	Waste collector	Waste transporter Waste reprocessor Waste recycler Landfill operator
RS 8:	Encouraging cross-border regional mobility of C&D waste that can increase the recycling rate	Federal government	State government Local government Industry association	Waste collector Waste transporter Waste recycler
RS 9:	Enhancing the management of cross-border regional mobility of C&D waste that can decrease the recycling rate	Federal government	State government Local government Industry association	Waste collector Waste transporter Landfill operator
RS 10:	Minimising the export of C&D waste overseas so as to retain more employment within Australia	Federal government	State government Local government Industry association	Waste transporter Waste reprocessor Waste recycler Landfill operator Recycled products consumer

Figure 7.21: Recommended optimisation strategies framework

a. Managing C&D waste as a critical sector of waste management in Australia

Based on the findings in relation to the management and cross-regional mobility of C&D waste in Australia in section 5.2 (Chapter 5) and section 7.2; C&D waste is the largest waste stream which contributes more than one-third of total solid waste generation in Australia. The generation of C&D waste is significantly greater than that of municipal solid waste (MSW) and commercial and industrial (C&I) core waste. However, the investments to C&D waste management from the administration and industry are far behind its competitors (i.e., MSW and C&I waste). The lack of attention on this issue will lead to great environmental impacts of C&D waste. Hence, managing C&D waste should be considered as a critical sector of waste management in Australia.

b. Applying an integrated waste management strategy to C&D waste

Based on the findings in section 5.2 (Chapter 5), masonry materials contribute about 83% of total generated C&D waste by weight regarding C&D waste materials. The remainder of C&D waste generated is comparatively less significant, consisting of multiple compositions such as metals, plastics, organics, paper and cardboard, glass, etc. These waste materials typically will be processed along with the same waste types generated from the MSW and C&I waste sectors. Given this trend, an integrated waste management strategy could be applied to these types of waste. The economic scale of waste treatment is thus a critical factor for the feasibility of recycling.

c. Developing a better recycled products market

According to the findings in section 5.3 (Chapter 5) and discussions in section 7.2 (Chapter 7), although the recycling rates of some C&D waste such as masonry materials, metals and glass are very high, their Economic Value Added (EVA) are relatively low. Recently, combustible materials such as organics, paper and cardboard and TLR are increasingly in demand as an alternative fuel in the market, which expands potential treatment methods. Since Australia is a market-based economy, the industry could be encouraged to determine methods of recycling C&D waste material to achieve the best economic outcomes by developing a better recycled products market.

d. Enhancing South Australia as the centre for waste recycling in Australia

According to the findings in section 5.3 (Chapter 5), due to the well-established industry, supply chains, market, regulations and business support from government, many destinations of waste transported cross-border for reprocessing/recycling are in South Australia. Since

Australia is a market-based economy and the Australian Constitution also enshrines freedom of trade between states and territories, the industry can determine C&D waste material streams flow to maximise profit. All these factors support the evidence that South Australia could be the waste recycling centre in Australia.

e. Enhancing cross-border management of regional landfilling in eastern regions in Australia

According to the findings in section 5.3 (Chapter 5), cross-regional mobility of C&D waste is quite dynamic in Australia's eastern regions including NSW, ACT, VIC and QLD. Particularly the masonry waste, normally processed or disposed of within the region, has been transported across-borders at these areas. In some situations, the destinations for waste disposal may not need to meet regulatory requirements in line with those in the regions where waste was originally generated. In other words, waste has been transported to other regions where they may not able to appropriately address the environmental risks by importing waste. This could increase potential community, environmental and public health impacts at the destination, as waste may not be treated appropriately and may contain harmful matter. Hence, it is necessary to tighten cross-border management in terms of regional landfilling in eastern regions in Australia.

f. Developing appropriate landfill levies for C&D waste

Based on the discussions in section 7.2.3, a critical reason for cross-regional mobility in disposing masonry waste outside of the region where this waste was originally generated is avoiding/reducing the landfill levy. Landfill levies significantly differ among eastern regions. For instance, the landfill levy for C&D waste in the metropolitan regions of NSW can be up to 140AUD/t, yet there is no landfill levy for this type of waste in neighbouring ACT. The difference in landfill levies provides incentives for transporters to select cheaper cross-border landfill destinations. Using cheaper landfill options interstate can give practitioners better economic outcomes; however, it can undermine the governments' approach to waste management and resource recovery, and it can also undermine the local market. Hence, it is recommended that state and territory authorities consider the consequences of C&D waste cross-regional mobility when developing landfilling levies.

g. Developing better management procedures for certain types of C&D waste such as metals, masonry waste and timber

The study evaluated environmental and economic impacts of C&D waste management, in particular in relation to cross-regional mobility of waste. Based on the results in sections 6.2

and 6.3 (Chapter 6), the environmental and economic impacts of certain C&D waste materials are more significant than other materials. For instance, steel, organics (timber), aluminium, copper, and paper and cardboard are major contributors to most environmental indicators, while other materials such as plastics, glass and TLR play less significant roles in contributing to environmental impacts. In terms of economic impacts, the findings show that waste collection and transportation and pre-processing contribute 52.1% of industry income, followed by recycling of masonry waste (19.7%), recycling of metals (13%), landfilling of masonry waste (7.4%), recycling of other unclassified waste (5%) and recycling of timber (1.1%). The contribution from other factors is minor (less than 2%). Therefore, certain C&D waste materials (i.e. masonry waste, metals, timber) should receive more attention when adopting waste management strategies.

h. Encouraging cross-regional mobility of C&D waste that can increase the recycling rate

Based on the scenario analyses in section 7.3, if recycling and landfilling rates are fixed, cross-regional mobility will not significantly affect environmental impacts with respect to most environmental indicators. However, if cross-regional mobility increases the recycling rate, the value of most environmental impact indicators decreases. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can reduce environmental impacts. Accordingly, if recycling and landfilling rates are fixed, cross-regional mobility will not significantly affect economic performance. However, if cross-regional mobility can increase the recycling rate, industry income will increase from 5.63 billion AUD to 7.10 billion AUD. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility activity can increase industry income. Therefore, cross-regional mobility of C&D waste can be recommended, if the activity increases the recycling rate.

i. Enhancing the management of cross-regional mobility of C&D waste that decreases the recycling rate

As discussed in section 7.3, if recycling and landfilling rates are fixed, cross-regional mobility will not significantly affect environmental impacts with respect to most environmental indicators. However, if the aim of cross-regional mobility is landfill, generated C&D waste in other regions, environmental impacts will increase. In other words, if cross-regional mobility of C&D waste increases the landfilling rate, cross-regional mobility will increase environmental impacts. If recycling and landfilling rates are fixed, cross-regional mobility will not significantly affect economic performance. However, if cross-regional mobility increases the landfilling rate, industry income will decrease from 7.10 billion AUD to 5.63 billion AUD. In other words, if cross-regional mobility of C&D waste aims to landfill the generated C&D waste in other regions rather than recycling such waste, cross-regional mobility activity will decrease industry income. Therefore, cross-regional mobility of C&D waste should be discouraged, if the activity decreases the recycling rate.

j. Minimising the export of C&D waste overseas so as to retain more employment within Australia

Based on social impacts assessment in the study (section 6.4 and section 7.3.3), the findings show that if a considerable amount of C&D waste generated involves cross-regional mobility, this regional mobility of C&D waste will generally decrease employment opportunities for managing waste (in regions that export their waste) and increase employment opportunities for managing C&D waste (in regions that import their waste). If a significant amount of C&D waste generated in Australia is transported for further processing in other countries, employment for managing C&D waste in Australia will decrease. Therefore, the export of C&D waste overseas should be minimised, if the industry wants to retain more employment within Australia.

7.5 Summary

This chapter presented the discussion based on the research findings, including characterisation of cross-regional mobility of C&D waste in Australia, benefits and impacts of C&D waste cross-regional mobility in Australia, and recommended optimisation strategies regarding the management of cross-regional mobility of C&D waste in Australia.

C&D waste management is recommended as a critical sector of waste management in Australia, as C&D waste is the largest waste stream which contributes more than one-third of total waste generation in Australia. An integrated waste management strategy could be developed for some types of C&D waste materials (metals, plastics, organics, paper and cardboard, glass), as the economic scale of waste treatment is a critical factor for evaluating the feasibility of recycling. Three main forms of C&D waste cross-regional mobility are evident in Australia: transport interstate for recycling, transport interstate for landfilling, and export overseas for reprocessing/recycling. Cross-regional mobility of C&D waste materials could be determined by several factors, including availability of facilities, landfill levies, regulatory requirements and markets.

The environmental impacts of C&D waste cross-regional mobility in Australia, economic impacts of C&D waste cross-regional mobility in Australia, and social impacts of C&D waste cross-regional mobility in Australia were also discussed. Cross-regional mobility of C&D waste has multiple impacts on the waste management sector in states involved in waste cross-regional mobility (including environmental, economic and social performance), as the movement of C&D waste from one region to another will affect all aspects of waste treatment. If recycling and landfilling rates are fixed, cross-regional mobility will not significantly affect the performance of economic or most environmental indicators. If cross-regional mobility of C&D waste can increase the recycling rate, cross-regional mobility can decrease environmental impacts, and thus increase industry income. Regarding the social aspect, if a significant amount of C&D waste generated in Australia is transported for further processing in other countries, employment for managing C&D waste will decrease. Therefore, cross-regional mobility of C&D waste is recommended, if the activity can increase the recycling rate. The export of C&D waste overseas should be minimised if the industry wants to retain more employment within Australia.

A series of optimisation strategies for the management of cross-regional mobility of C&D waste in Australia has also been discussed and recommended.

To recap them:

a. Considering C&D waste management as a critical sector of waste management in Australia;
b. Applying an integrated waste management strategy to C&D waste;
c. Developing a better recycled products market;
d. Enhancing South Australia as the centre for waste recycling in Australia;
e. Tightening cross-border management in terms of regional landfilling in eastern regions in Australia;
f. Developing appropriate landfill levies for C&D waste;
g. Paying more attention to managing certain C&D waste;
h. Encouraging cross-regional mobility of C&D waste that can increase the recycling rate;
I. Tightening the management of cross-regional mobility of C&D waste that can decrease the recycling rate;
j. Minimising the export of C&D waste overseas if the industry wants to retain more employment within Australia.

Chapter 8. Conclusion

As highlighted in previous studies, the ever-increasing generation of C&D waste has raised serious concerns about threats to sustainable development worldwide. Although the amount of C&D waste generated in Australia may not appear to be much when compared with many other countries, it is still the most significant waste stream of all solid waste generated. Massive amounts of C&D waste cause a series of environmental issues as a result of raw material resource waste, energy consumption, water and soil pollution and land occupation. Processing waste also requires significant financial investment and labour resources. Driven by multiple incentives, C&D waste is transported from its origin to other regions for further treatment. In fact, large amounts of waste have been transported interstate for pre-processing or to landfill in Australia in recent years. However, as discussed in previous chapters, this issue has been largely overlooked. A novel perspective (i.e. expanding the traditional local-closed model to a cross-regional mobility model that addresses impacts of cross-regional mobility of the waste) was developed to address the impacts of cross-regional mobility on waste.

This chapter consists of four sections: the first section presents the main findings from the study and demonstrates how those findings respond to the aim and objectives of the study outlined in section 1.4. The main recommendations arising from the study will also be outlined. The second section presents an argument for broader theoretical and practical implications of the research. The third discusses the limitations and opportunities for future research, and the fourth and final section offers some closing remarks.

8.1 Findings

The research presented in this thesis has responded to the aim and objectives as outlined in the introductory chapter. The review of existing literature on C&D waste research in the last three decades, demonstrates the opportunities available to address the impacts of cross-regional mobility of C&D waste in Australia with respect to environmental, economic and social aspects. Sufficient data was collected through a comprehensive literature review, and a series of desktop surveys, site surveys, expert interviews, expert seminars, and professional databases to address all objectives. A novel impacts assessment methodology aligned with a series of databases developed in Chapter 4, demonstrated that cross-regional mobility of C&D waste has multiple impacts on waste management systems in Australia.

8.1.1 Objective 1

To investigate the management and cross-regional mobility of C&D waste by developing a cross-regional C&D waste material network for Australia

Previous studies indicate that some C&D waste was treated interstate or overseas; however, accurate data on the composition of different wastes is not available. The answers to this question can establish a baseline of cross-regional mobility scenarios of C&D waste in Australia. It is believed that this research is a first in Australia to quantitatively reveal cross-regional mobility of C&D waste including categories, amounts, and travel routes of C&D waste treated interstate or overseas.

Based on a well-developed methodology (see section 4.3, Chapter 4), cross-regional mobility of C&D waste in Australia was quantified by a series of desktop surveys, site surveys, expert seminar and expert interviews. Similarly, cross-regional mobility of C&D waste in Australia was mapped against the generated data and the results were detailed in Chapter 5 (Part 1).

These findings suggested three main forms of C&D waste cross-regional mobility in Australia including:

- transport to another state for recycling;
- transport to another state for landfilling; and
- export overseas for reprocessing/recycling.

South Australia was identified as the exemplary centre for C&D waste cross-regional mobility for recycling in Australia, receiving C&D waste materials from the Northern Territory, New South Wales, West Australia and Victoria.

Cross-regional mobility of waste is quite dynamic in Australia's eastern regions (New South Wales (NSW), the Australia Capital Territory (ACT), Victoria (Vic) and Queensland (Qld)) where the findings show that NSW is a major player in transporting its C&D waste—particularly masonry waste—to its neighbours, where adjoining states or territories have much lower disposal fees.

For the whole of Australia, although most masonry waste is processed or disposed of within the regions where it was generated, a considerable amount was transported cross-border for landfill whereas a minor amount was sent to other regions for reprocessing/recycling. Waste materials such as metals, plastics, and paper and cardboard are more likely to be reprocessed in other regions, or even overseas.

8.1.2 Objective 2

To develop a novel methodology to assess the impacts of cross-regional mobility of C&D waste by considering economic-social-environmental aspects

The literature revealed that there are several ways to assess C&D waste management performance, and these provided an opportunity to develop a new methodology to assess the impacts of cross-regional mobility of C&D waste, by considering the economic-social-environmental aspects. By adopting this approach, this study has expanded C&D waste research theory from a local-closed issue to a cross-regional mobility issue.

A life cycle thinking theory-based methodology was developed (see section 4.4, Chapter 4) to fill the gap in knowledge caused by the lack of a suitable approach to evaluate the impacts of cross-regional mobility of C&D waste.

The impacts assessment model framework consisted of the following steps:

a. Setting the system boundary;
b. Identifying the key life cycle stages and activities;
c. Identifying the inputs/outputs for each activity and stage;
d. Identifying the impact factors;
e. Collecting data and conducting the inventory analysis;
f. Calculating and conducting the scenario analysis; and
g. Interpreting the results.

Sufficient data, including background data and foreground data, were collected based on multiple sources: the literature review, site surveys, expert interviews and professional databases from *GaBi professional*.

Results in Chapter 6 clearly demonstrate that cross-regional mobility of the C&D waste has multiple impacts, including environmental, economic and social impacts in Australia.

Environmental impacts

Based on the analysis in Chapter 7 (section 7.3), for most environmental indicators (EI-1 to EI-11), steel is a critical contributor to environmental impacts. Organics (timber), aluminium, copper, and paper and cardboard are also major contributors to environmental indicators. Landfilling of masonry materials, paper and cardboard, and organics dominated the indicator of environmental impacts—land occupation. In other words, C&D waste materials such as plastics, glass, textiles, leather and rubber (TLR) play less significant roles in contributing to environmental impacts.

The results demonstrated that if recycling and landfilling rates are fixed, cross-regional mobility will not significantly affect environmental impacts regarding most environmental indicators. However, if cross-regional mobility can increase the recycling rate, the value of most environmental impact indicators will decrease. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility can decrease environmental impacts. In contrast, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will increase environmental impacts.

Economic impacts

Industry income was selected as the indicator for economic impacts of cross-regional mobility of C&D waste in Australia. Analysis of economic impacts in Chapter 7 (section 7.3.2) revealed that waste collection and transportation and pre-processing contribute 52.1% of industry income, followed by recycling of masonry waste (19.7%), metals (13%), landfilling of masonry waste (7.4%), recycling of other unclassified waste (5%), and recycling of timber (1.1%). The contribution from other factors is minor (less than 2% in total).

Based on the scenario analysis outlined in Chapter 7 (subsection 7.3.2.2), the findings suggest that if recycling and landfilling rates are fixed, cross-regional mobility will not significantly affect economic performance. However, if cross-regional mobility can increase the recycling rate, industry income will increase from 5.63 billion AUD to 7.10 billion AUD. In other words, if cross-regional mobility of C&D waste can increase the recycling rate of waste, cross-regional mobility activity can increase industry income. In contrast, if cross-regional mobility of C&D waste increases the landfilling rate of waste, cross-regional mobility will decrease industry income.

Social impacts

As cross-regional mobility of C&D waste affects the amount of waste being managed in the regions where waste originated and regions that imported waste, social impacts regarding employment are affected by the cross-regional issue.

Based on social impacts assessment and analysis conducted in Chapter 6 (section 6.4) and Chapter 7 (section 7.3), it is evident that if a considerable portion of C&D waste generated involved cross-regional mobility, then cross-regional mobility of C&D waste will generally reduce employment opportunities for managing waste in regions that export waste, and increase employment opportunities for managing waste in regions that import waste. In particular, if a significant portion of C&D waste generated in Australia is transported to another country for further processing, the employment rate for the management of C&D waste in Australia will decrease. Accordingly, the exporting of C&D waste overseas should be minimised, if the industry wants to retain employment within Australia.

8.1.3 Objective 3

To provide recommendations to Australian C&D waste management departments to decide whether or not to encourage cross-regional mobility of waste, and at what level.

Cross-regional mobility of C&D waste management is not necessarily a negative phenomenon for both regions involved and may well have some positive effects if managed appropriately. By comparing different scenarios, optimisation strategies could be identified to help government and industry make informed decisions for sustainable management of C&D waste. Based on the findings of the study, ten optimisation strategies have been recommended for the management of cross-regional mobility of C&D waste in Australia: (see section 7.4):

1. Considering the management of C&D waste as a critical sector of waste management in Australia.
2. Applying an integrated waste management strategy to C&D waste.
3. Developing a better recycled products market.
4. Enhancing the strength of South Australia as the centre of waste recycling in Australia.
5. Improving better border management of cross-regional landfilling in the eastern regions of Australia.
6. Developing appropriate landfill levies for C&D waste.

7. Developing better management procedures for certain types of C&D waste such as metals, masonry waste and timber.
8. Encouraging cross-regional mobility of C&D waste that increases the recycling rate.
9. Improving the management of cross-regional mobility of C&D waste that decreases the recycling rate.
10. Minimising export of C&D waste overseas so as to retain employment within Australia.

8.2 Theoretical and practical implications

This study has delivered significant implications for understanding the cross-regional mobility of C&D waste and related impacts. Theoretically, this research offers an innovative perspective on C&D waste management by expanding C&D waste management theory from the local-closed loop to a cross-regional network level. With respect to methodology, this study improves management performance assessment methodologies for C&D waste by considering environmental, economic and social impacts of cross-regional mobility of waste. The novel assessment approaches, indicators, calculation methods and databases developed in the study will make a contribution to management performance assessment methodologies of C&D waste. Practically, this study provides recommendations for waste management departments to develop strategies to address cross-regional mobility of C&D waste issues. In addition, the findings will assist local C&D waste management service providers to optimise their product categories and resource investments, and the general public will in turn benefit from such optimisation activities conducted by governments and the C&D waste industry.

8.2.1 Theoretical and practical implications

Firstly, regarding theoretical contributions, this study expands C&D waste management theory form the local-closed loop to a cross-regional network level. As reviewed in Chapter 2, hundreds of studies have been conducted on C&D waste from various disciplines, such as environmental science and engineering, material science, C&D waste management, etc. In particular, significant studies have been conducted to track material flows of C&D waste, which is about understanding the materials that flow from waste generation to final disposal. As the majority of C&D waste comes from heavyweight and low unit economic value materials, this make the transportation of waste inefficient. Traditionally, there is an expectation that C&D waste is treated and recycled at local recycling facilities or disposed of in local landfill. As a result, previous studies adopted a local-closed theory to study C&D waste. In fact, multiple incentives cause C&D waste to be transported from the region where it was originally generated to other regions for further treatment. This cross-regional mobility will affect the amount of C&D waste being managed in regions that export and import waste, thereby affecting the environmental, economic and social performance of the system. However, this cross-regional mobility issue has been overlooked in previous studies, and there is little knowledge about cross-regional mobility of C&D waste and related impacts. This study is the first to propose the cross-regional mobility of C&D waste concept (Chapter 4, section 4.2) and to conduct an investigation of cross-regional mobility of C&D waste in Australia (Chapter 5). Hence, this research contributes to the theoretical development of C&D waste management by expanding the system boundary of traditional research.

Secondly, this study also contributes to the theoretical development of management performance assessment methodologies by considering environmental, economic and social impacts of cross-regional mobility of C&D waste. Chapter 3 systematically reviewed the approaches to impacts assessment of C&D waste management in previous studies. Significant studies have been conducted to develop models and indicators for assessing management performances, particularly impacts of C&D waste. A considerable number of previous studies have used well-developed methods such as LCA and SD for assessing impacts of C&D waste management activities; while some studies refined an existing method or created an original model involving performance assessment indicators. By reviewing these studies, a number of well-developed models for environmental impacts assessment were evident, but there are only a few methods for economic and social impacts assessment. Social impacts assessment often concern issues like wages, health and safety, and access to education. The barriers to conducting adequate social impact assessment lie in the fact that the issues at stake are wide-ranging and often difficult to quantify in a meaningful way. Similarly, due to the limitation in research perspectives, previous studies viewed the management of C&D waste as a local-closed issue, and they did not consider particular parameters for the cross-regional mobility in C&D waste management when they developed the evaluation criteria. Based on the systematic review in Chapter 3, this study developed a novel methodology to quantitatively assess environmental, economic and social impacts of cross-regional mobility of C&D waste. The environmental impacts assessment comprehensively covered twelve indicators based on the classic CML 2015 method. Meanwhile, the study employed industry income as performance indicator for the economic impacts assessment, and it adopted employment opportunity as performance indicator for the social impacts assessment. The selection of these indicators enabled the quantitative impacts assessment of cross-regional mobility of C&D waste to be feasible and this can provide guidelines for future studies.

Thirdly, the study also contributed to the development of a fundamental LCA database by developing multiple databases, including those for cross-regional mobility of C&D waste in Australia, environmental impacts assessment, economic impacts assessment, and social impacts assessment. A review of previous studies suggested that there is a shortage of fundamental LCA research in Australia and a lack of localised impacts characterisation data for assessing the management performance of C&D waste in Australia. The most demanding task in performing an LCA is data collection, and research cannot be completed if there is no available data. The lack of data indeed presents significant challenges to previous LCA research. Careful selection of data sources can enhance data credibility. By applying multiple approaches such as desktop surveys, site surveys, expert interviews, expert seminars and accessing professional databases, this study developed a series of databases which can be used as foreground and background data for future LCA studies. Apart from the data collected in this research, results produced in Chapters 5 and 6 can also serve as fundamental data for future studies.

8.2.2 Practical implications

As waste management and resource recovery is a significant sector in relation to the environment, the economy and society in Australia, this study is expected to also have practical contributions for the C&D waste management sector.

Firstly, the results of management and cross-regional mobility of C&D waste in Chapter 5 (Part 1) provide valuable information for governmental departments to develop waste management plans such as recycling facilities and landfill, etc. Waste management enterprises can also use this information for business planning. For instance, they can adjust their production lines and make future revisions according to critical C&D waste materials information revealed in this study.

Secondly, the research provides detailed data for the environmental, economic and social impacts outlined in Chapter 6. The waste management government department can set environmental prevention tasks concentrating on critical aspects relating to environmental issues and waste management enterprises can invest in sectors lacking investment, according to the findings revealed in this research.

Thirdly, ten optimisation strategies were recommended for the management of cross-regional mobility of C&D waste in Australia in Chapter 7. There are many stakeholders in C&D waste management, including the federal government, state governments, local governments, waste generators, waste collectors, waste transporters, waste reprocessors, waste recyclers, landfill operators, recycled products consumers, industry associations and so on. When proposing the recommendations, the study also indicated the initiator (who initiates the measure), participants (involved in the measure), and subject (who undertake the measure) for each optimisation strategy. Based on these optimisation strategies, the authority could further strengthen legislation for C&D waste management.

8.3 Limitations and opportunities for future research

Although significant efforts have been made to conduct the research, there are three main limitations in the study.

Firstly, due to budget and resource limitations, site surveys and expert interviews were mainly conducted in South Australia. Similarly, the experts interviewed were from C&D nationwide waste recycling companies based across Australia. This is compensated to a certain degree by a series of site visits to recycling plants as well as communication with C&D waste management experts in NSW, VIC, and QLD prior to the formal surveys. There is a need to better understand how cross-regional mobility of C&D waste affects waste management networks in Australia. This new research will expand the existing evaluation model and enable the model to better test the resilience of the system.

Secondly, there is a limitation on the selection of social impact assessment indicators in this study. As discussed in the literature review and methodology chapters, the indicators of social impact assessment in previous studies are wide-ranging and often difficult to be quantified in a meaningful way. By considering feasibility and data availability, this study used a single indicator, namely employment opportunity, as the indicator for a quantitative social impacts assessment. In future research, more social indicators could be taken into consideration to allow a more specific social assessment of impacts derived from cross-regional mobility of C&D waste.

Thirdly, there is limited availability of localised background data for environmental impacts assessment in the research. As discussed in the methodology chapter, there are a series of background data required in the calculation, such as impact factors in relation to the electricity grid, energy consumption, and emissions from each waste treatment process, and also impact factors in relation to processing C&D waste material. The background data on environmental impact factors used in the research were mainly exported from *GaBi Professional* software, which covers a range of environmental impact databases (including *Ecoinvent*), and constituted the best available software with a wide range of LCA data for the researcher. However, there is a shortage of Australian localised environmental impact characterisation indicators data for meeting the demands of all sectors, as fundamental LCA research in Australia was not adequate and fundamental localised data has not been established yet. This research had to compromise by adopting available LCA data in other countries to overcome the shortage of localised data. Therefore, there is a significant demand for fundamental LCA research aimed at developing basic LCA data in Australia, particularly in the C&D waste sector.

8.4 Closing remarks

This study was motivated by the increasing challenges caused by the massive generation of C&D waste worldwide. It is essential that we understand the consequences of various activities imposed on waste management systems and develop measures to address these issues. This study investigated the impacts of cross-regional mobility of C&D waste in Australia in terms of environmental, economic and social aspects. Traditionally, cross-regional mobility of C&D waste was not considered in previous theories, as the majority of C&D waste was heavyweight and low unit economic value materials, which made the transportation of C&D waste inefficient. These types of waste are normally treated and recycled at local recycling facilities or disposed of in local landfill. The management of C&D waste was usually viewed as a local-closed issue, and the system boundary was limited to the regional level. However, many different factors such as availability of facilities, landfill levies and the recycling market meant that a considerable portion of C&D waste was transported from the region where it originated to other regions. This thesis has made it clear that C&D waste is not always handled in the region where it originated but rather transported (cross-regional mobility) in ways that achieved the best economic outcomes for its owners. However, if economic outcomes are the main goal, then this is likely to result in other significant concerns, for example, waste transported to a region that may not have the expertise to appropriately identify and handle environmental risks created by imported waste. This could lead to an increase in community, environmental and public health impacts at that destination, as waste may not have been treated appropriately to ensure health and safety for the community.

Analysis carried out in this study indicated that the structure of this system is extremely complex and dynamic, thereby making it complicated and difficult to understand. Any minor changes in the system could result in significant consequences accordingly, it is important that due consideration be given to all waste management activities. To simply disallow cross-regional mobility may well lead to the loss of current established practices that lead to the development of a resilient network that contributes to a sustainable society.

References

Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Owolabi, H. A., Alaka, H. A.,…Kadiri, K. O. (2016). Reducing waste to landfill: A need for cultural change in the UK construction industry. *Journal of Building Engineering, 5*, 185-193. doi: 10.1016/j.jobe.2015.12.007

Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. *Resources Conservation and Recycling, 102*, 101-112. doi: 10.1016/j.resconrec.2015.06.001

Al-Sari, M. I., Al-Khatib, I. A., Avraamides, M., & Fatta-Kassinos, D. (2012). A study on the attitudes and behavioural influence of construction waste management in occupied Palestinian territory. *Waste Management & Research, 30*(2), 122-136. doi: 10.1177/0734242x11423066

Alexeev, M., & Chernyavskiy, A. (2018). A tale of two crises: Federal transfers and regional economies in Russia in 2009 and 2014–2015. *Economic Systems*, *42*(2), 175-185.

Anastasiou, E., Filikas, K. G., & Stefanidou, M. (2014). Utilization of fine recycled aggregates in concrete with fly ash and steel slag. *Construction and Building Materials, 50*, 154-161. doi: 10.1016/j.conbuildmat.2013.09.037

Arulrajah, A., Ali, M. M. Y., Disfani, M. M., & Horpibulsuk, S. (2014). Recycled-glass blends in pavement base/subbase applications: Laboratory and field evaluation. *Journal of Materials in Civil Engineering, 26*(7), 12. doi: 10.1061/(asce)mt.1943-5533.0000966

Arulrajah, A., Piratheepan, J., Disfani, M. M., & Bo, M. W. (2013). Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *Journal of Materials in Civil Engineering, 25*(8), 1077-1088. doi: 10.1061/(asce)mt.1943-5533.0000652

Barthel, S., Folke, C., & Colding, J. (2010). Social–ecological memory in urban gardens: Retaining the capacity for management of ecosystem services. *Global Environmental Change*, *20*(2), 255-265. doi: https://doi.org/10.1016/j.gloenvcha.2010.01.001

Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2006). A benefit-cost analysis on the economic feasibility of construction waste minimisation: The case of Malaysia. *Resources Conservation and Recycling, 48*(1), 86-98. doi: 10.1016/j.resconrec.2006.01.004

—— (2007). Implementation of waste management and minimisation in the construction industry of Malaysia. *Resources Conservation and Recycling, 51*(1), 190-202. doi: 10.1016/j.resconrec.2006.09.004

Belagraa, L., Beddar, M., & Bouzid, A. (2017). Mabble fillers effect on the mechanical performance of a recycled aggregate concrete. *Environmental Engineering and Management Journal, 16*(1), 197-204.

Benoît-Norris, C., Vickery-Niederman, G., Valdivia, S., Franze, J., Traverso, M., Ciroth, A., … Mazijn, B. (2011). Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. *The International Journal of Life Cycle Assessment, 16*(7), 682-690.

Bergersen, O., & Haarstad, K. (2014). Treating landfill gas hydrogen sulphide with mineral wool waste (MWW) and rod mill waste (RMW). *Waste Management, 34*(1), 141-147. doi: 10.1016/j.wasman.2013.09.012

Bergsdal, H., Bohne, R. A., & Brattebo, H. (2007). Projection of construction and demolition waste in Norway. *Journal of Industrial Ecology, 11*(3), 27-39. doi: 10.1162/jiec.2007.1149

Bergsdal, H., Brattebo, H., Bohne, R. A., & Mueller, D. B. (2007). Dynamic material flow analysis for Norway's dwelling stock. *Building Research and Information, 35*(5), 557-570. doi: 10.1080/09613210701287588

Bernardo, M., Gomes, M. C., & de Brito, J. (2016). Demolition waste generation for development of a regional management chain model. *Waste Management, 49*, 156-169. doi: 10.1016/j.wasman.2015.12.027

Bjegovic, D., Stirmer, N., & Serdar, M. (2012). Durability properties of concrete with blended cements. *Materials and Corrosion-Werkstoffe Und Korrosion, 63*(12), 1087-1096. doi: 10.1002/maco.201206699

Blengini, G. A. (2009). Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Building and Environment, 44*(2), 319-330. Doi: https://doi.org/10.1016/j.buildenv.2008.03.007

Blengini, G. A., & Garbarino, E. (2010). Resources and waste management in Turin (Italy): The role of recycled aggregates in the sustainable supply mix. *Journal of Cleaner Production, 18*(10-11), 1021-1030. doi: 10.1016/j.jclepro.2010.01.027

Bohne, R. A., Brattebo, H., & Bergsdal, H. (2008). Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level. *Journal of Industrial Ecology, 12*(1), 52-68. doi: 10.1111/j.1530-9290.2008.00013.x

Boote, D. N., & Beile, P. (2005). Scholars before researchers: On the centrality of the dissertation literature review in research preparation. *Educational Researcher*, *34*(6), 3-15. doi: https://doi.org/10.3102/0013189X034006003

Brattebo, H., Bergsdal, H., Sandberg, N. H., Hammervold, J., & Muller, D. B. (2009). Exploring built environment stock metabolism and sustainability by systems analysis approaches. *Building Research and Information, 37*(5-6), 569-582. doi: 10.1080/09613210903186901

Bravo, M., de Brito, J., Pontes, J., & Evangelista, L. (2015). Durability performance of concrete with recycled aggregates from construction and demolition waste plants. *Construction and Building Materials, 77*, 357-369. doi: 10.1016/j.conbuildmat.2014.12.103

Bringezu, S., & Moriguchi, Y. (2002). Material flow analysis, *A handbook of industrial ecology*, pp. 79-90. Edward Elgar Publishing.

Butera, S., Christensen, T. H., & Astrup, T. F. (2015). Life cycle assessment of construction and demolition waste management. *Waste Management, 44*, 196-205. doi: 10.1016/j.wasman.2015.07.011

Cabalar, A. F., Abdulnafaa, M. D., & Karabash, Z. (2016). Influences of various construction and demolition materials on the behavior of clay. *Environmental Earth Sciences, 75*(9), 9. doi: 10.1007/s12665-016-5631-4

Chan, K. S., Dang, V. Q., Lai, J. T., & Yan, I. K. (2011). Regional capital mobility in China: 1978–2006. *Journal of International Money and Finance*, *30*(7), 1506-1515. doi: https://doi.org/10.1016/j.jimonfin.2011.08.001

Chau, C. K., Xu, J. M., Leung, T. M., & Ng, W. Y. (2017). Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building. *Applied Energy, 185*, 1595-1603. doi: 10.1016/j.apenergy.2016.01.019

Cheng, J. C., & Ma, L. Y. (2013). A BIM-based system for demolition and renovation waste estimation and planning. *Waste Management*, *33*(6), 1539-1551. doi: https://doi.org/10.1016/j.wasman.2013.01.001

Choudhary, A., Shah, V., & Bishnoi, S. (2016). Effect of low cost fillers on cement hydration. *Construction and Building Materials, 124*, 533-543. doi: 10.1016/j.conbuildmat.2016.07.088

Chung, S. S., & Lo, C. W. H. (2003). Evaluating sustainability in waste management: The case of construction and demolition, chemical and clinical wastes in Hong Kong. *Resources Conservation and Recycling, 37*(2), 119-145. doi: 10.1016/s0921-3449(02)00075-7

Cochran, K., Townsend, T., Reinhart, D., & Heck, H. (2007). Estimation of regional building-related C&D debris generation and composition: Case study for Florida, US. *Waste Management, 27*(7), 921-931. doi: 10.1016/j.wasman.2006.03.023

Coelho, A., & de Brito, J. (2011). Generation of construction and demolition waste in Portugal. *Waste Management & Research, 29*(7), 739-750. doi: 10.1177/0734242x11402253

—— (2013). Economic viability analysis of a construction and demolition waste recycling plant in Portugal -- part I: Location, materials, technology and economic analysis. *Journal of Cleaner Production, 39*, 338-352. doi: 10.1016/j.jclepro.2012.08.024

Corinaldesi, V., & Moriconi, G. (2009). Behaviour of cementitious mortars containing different kinds of recycled aggregate. *Construction and Building Materials, 23*(1), 289-294. doi: 10.1016/j.conbuildmat.2007.12.006

Correia, J. R., de Brito, J., & Pereira, A. S. (2006). Effects on concrete durability of using recycled ceramic aggregates. *Materials and Structures, 39*(2), 169-177. doi: 10.1617/s11527-005-9014-7

da Rocha, C. G., & Sattler, M. A. (2009). A discussion on the reuse of building components in Brazil: An analysis of major social, economical and legal factors. *Resources Conservation and Recycling, 54*(2), 104-112. doi: 10.1016/j.resconrec.2009.07.004

da Silva, V. M., Gois, L. C., Duarte, J. B., da Silva, J. B., & Acchar, W. (2014). Incorporation of ceramic waste into binary and ternary soil-cement formulations for the production of solid bricks. *Materials Research-Ibero-American Journal of Materials, 17*(2), 326-331. doi: 10.1590/s1516-14392014005000014

Dahlbo, H., Bacher, J., Lahtinen, K., Jouttijarvi, T., Suoheimo, P., Mattila, T., . . . Saramaki, K. (2015). Construction and demolition waste management -- a holistic evaluation of environmental performance. *Journal of Cleaner Production, 107*, 333-341. doi: 10.1016/j.jclepro.2015.02.073

De Moraes, P. J., Allison, J., Robinson, J. A., Baldo, G. L., Boeri, F., & Borla, P. (2013). Life cycle assessment (LCA) and environmental product declaration (EPD) of an immunological product for boar taint control in male pigs. *Journal of Environmental Assessment Policy and Management*, *15*(01), 1350001. doi: https://doi.org/10.1142/S1464333213500014

Dee, Department of the Environment and Energy, 2018, *National Waste Report 2018*, Available at: https://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2018.

Dejkovski, N. (2016). Assessing the environmental performance of construction materials testing using EMS: An Australian study. *Waste Management, 56*, 359-366. doi: 10.1016/j.wasman.2016.07.016

Delay, M., Lager, T., Schulz, H. D., & Frimmel, F. H. (2007). Comparison of leaching tests to determine and quantify the release of inorganic contaminants in demolition waste. *Waste Management, 27*(2), 248-255. doi: 10.1016/j.wasman.2006.01.013

Denyes, M. J., Parisien, M. A., Rutter, A., & Zeeb, B. A. (2014). Physical, chemical and biological characterization of six biochars produced for the remediation of contaminated sites. *Jove-Journal of Visualized Experiments,* (93), 1-12. doi: 10.3791/52183

Ding, Z. K., Wang, Y. F., & Zou, P. X. W. (2016). An agent based environmental impact assessment of building demolition waste management: Conventional versus green management. *Journal of Cleaner Production, 133*, 1136-1153. doi: 10.1016/j.jclepro.2016.06.054

Ding, Z. K., Yi, G. Z., Tam, V. W. Y., & Huang, T. Y. (2016). A system dynamics-based environmental performance simulation of construction waste reduction management in China. *Waste Management, 51*, 130-141. doi: 10.1016/j.wasman.2016.03.001

Diyamandoglu, V., & Fortuna, L. M. (2015). Deconstruction of wood-framed houses: Material recovery and environmental impact. *Resources Conservation and Recycling, 100*, 21-30. doi: 10.1016/j.resconrec.2015.04.006

Dosho, Y. (2007). Development of a sustainable concrete waste recycling system -- Application of recycled aggregate concrete produced by aggregate replacing method. *Journal of Advanced Concrete Technology, 5*(1), 27-42. doi: 10.3151/jact.5.27

Dreyer, L., Hauschild, M., & Schierbeck, J. (2006). A framework for social life cycle impact assessment (10 pp.). *The International Journal of Life Cycle Assessment*, *11*(2), 88-97.

Du, H., Li, B., Brown, M. A., Mao, G., Rameezdeen, R., & Chen, H. (2015). Expanding and shifting trends in carbon market research: A quantitative bibliometric study. *Journal of Cleaner Production, 103*, 104-111. doi: https://doi.org/10.1016/j.jclepro.2014.05.094

Duan, H., Yu, D. F., Zuo, J., Yang, B., Zhang, Y. K., & Niu, Y. N. (2016). Characterization of brominated flame retardants in construction and demolition waste components: HBCD and PBDEs. *Science of the Total Environment, 572*, 77-85. doi: 10.1016/j.scitotenv.2016.07.165

Duran, X., Lenihan, H., & O'Regan, B. (2006). A model for assessing the economic viability of construction and demolition waste recycling -- the case of Ireland. *Resources Conservation and Recycling, 46*(3), 302-320. doi: 10.1016/j.resconrec.2005.08.003

EC, European Commission, 2017, Construction and demolition waste, waste streams, environment. Available at http://ec.europa.eu/environment/waste/construction_demolition.htm (2017)

EC, European Commission, 2019, Construction and demolition waste, waste streams, environment. Available at http://ec.europa.eu/environment/waste/construction_demolition.htm (2019)

Engelsen, C. J., van der Sloot, H. A., & Petkovic, G. (2017). Long-term leaching from recycled concrete aggregates applied as sub-base material in road construction. *Science of the Total Environment, 587*, 94-101. doi: 10.1016/j.scitotenv.2017.02.052

Erkman, S. (1997). Industrial ecology: An historical view. *Journal of Cleaner Production, 5*(1-2), 1-10. doi: https://doi.org/10.1016/S0959-6526(97)00003-6

Esa, M. R., Halog, A., & Rigamonti, L. (2017). Strategies for minimizing construction and demolition wastes in Malaysia. *Resources Conservation and Recycling, 120*, 219-229. doi: 10.1016/j.resconrec.2016,12.014

Esin, T., & Cosgun, N. (2007). A study conducted to reduce construction waste generation in Turkey. *Building and Environment, 42*(4), 1667-1674. doi: 10.1016/j.buildenv.2006.02.008

Evangelista, L., & de Brito, J. (2017). Flexural behaviour of reinforced concrete beams made with fine recycled concrete aggregates. *KSCE Journal of Civil Engineering, 21*(1), 353-363. doi: 10.1007/s12205-016-0653-8

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of science, and Google scholar: Strengths and weaknesses. *The FASEB Journal, 22*(2), 338-342.

Fava, J. A. (Ed.). (1993). *A conceptual framework for life cycle impact assessment*. Society of Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education.

Ferguson, D. W., & Male, J. W. (1980). The water-polltion potential from demolition waste-disposal. *Journal of Environmental Science and Health Part a-Environmental Science and Engineering, 15*(6), 545-559. doi: https://doi.org/10.1080/10934528009374949

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H. J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment*, *11*(2), 80-85.

Frischknecht, R., Jungbluth, N., Althaus, H. J., Bauer, C., Doka, G., Dones, R., ... & Loerincik, Y. (2007). Implementation of life cycle impact assessment methods.

Frischknecht, R., Wyss, F., Knöpfel, S. B., Lützkendorf, T., & Balouktsi, M. (2015). Cumulative energy demand in LCA: The energy harvested approach. *The International Journal of Life Cycle Assessment*, *20*(7), 957-969. doi: http://dx.doi.org/10.1007/s11367-016-1073-1

Galvin, A. P., Ayuso, J., Jimenez, J. R., & Agrela, F. (2012). Comparison of batch leaching tests and influence of pH on the release of metals from construction and demolition wastes. *Waste Management, 32*(1), 88-95. doi: 10.1016/j.wasman.2011.09.010

Gao, D. Y., Zhang, L., & Nokken, M. (2017). Mechanical behavior of recycled coarse aggregate concrete reinforced with steel fibers under direct shear. *Cement & Concrete Composites, 79*, 1-8. doi: 10.1016/j.cemconcomp.2017.01.006

Garcia-Gonzalez, J., Rodriguez-Robles, D., Juan-Valdes, A., Moran-del Pozo, J. M., & Guerra-Romero, M. I. (2014). Pre-saturation technique of the recycled aggregates: Solution to the water absorption drawback in the recycled concrete manufacture. *Materials, 7*(9), 6224-6236. doi: 10.3390/ma7096224

García, R., & Freire, F. (2014). Carbon footprint of particleboard: A comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. *Journal of Cleaner Production*, *66*, 199-209. doi: https://doi.org/10.1016/j.jclepro.2013.11.073

GISA, Green Industries SA, 2019, Government of South Australia, South Australia's recycling activity survey 2017 – 2018 report. Available at: https://www.greenindustries.sa.gov.au/SArecycling.

Godskesen, B., Hauschild, M., Rygaard, M., Zambrano, K., & Albrechtsen, H. J. (2012). Life cycle assessment of central softening of very hard drinking water. *Journal of Environmental Management*, *105*, 83-89. doi: https://doi.org/10.1016/j.jenvman.2012.03.030

Goedkoop, M., & Spriensma, R. (1999). The Eco-indicator 99: A damage oriented method for life cycle impact assessment methodology. *PRé Consultants, Amersfoort*. Netherlands.

Goedkoop, M., De Schryver, A., Oele, M., Durksz, S., & de Roest, D. (2008). Introduction to LCA with SimaPro 7. *PRé Consultants, The Netherlands*.

Gomes, C. F. S., Nunes, K. R. A., Xavier, L. H., Cardoso, R., & Valle, R. (2008). Multicriteria decision making applied to waste recycling in Brazil. *Omega-International Journal of Management Science, 36*(3), 395-404. doi: 10.1016/j.omega.2006.07.009

Gomes, P. C. C., Ulsen, C., Pereira, F. A., Quattrone, M., & Angulo, S. C. (2015). Comminution and sizing processes of concrete block waste as recycled aggregates. *Waste Management, 45*, 171-179. doi: 10.1016/j.wasman.2015.07.008

Gomez-Meijide, B., Perez, I., & Pasandin, A. R. (2016). Recycled construction and demolition waste in cold asphalt mixtures: Evolutionary properties. *Journal of Cleaner Production, 112*, 588-598. doi: 10.1016/j.jclepro.2015.08.038

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, *26*(2), 91-108.

Gualtieri, A. F. (2013). Recycling asbestos-containing material (ACM) from construction and demolition waste (CDW). In: *Handbook of recycled concrete and demolition waste* (pp. 500-525). Woodhead Publishing.

Guinée, J. B., & Lindeijer, E. (Eds.). (2002). *Handbook on life cycle assessment: operational guide to the ISO standards*(Vol. 7). Springer Science & Business Media.

Hao, J. L., Hills, M. J., & Tam, V. W. Y. (2008). The effectiveness of Hong Kong's Construction Waste Disposal Charging Scheme. *Waste Management & Research, 26*(6), 553-558. doi: 10.1177/0734242x07085345

Heininen, L. (2005). Impacts of globalization, and the circumpolar north in world politics. *Polar Geography*, *29*(2), 91-102.

Hiete, M., Stengel, J., Ludwig, J., & Schultmann, F. (2011). Matching construction and demolition waste supply to recycling demand: A regional management chain model. *Building Research and Information, 39*(4), 333-351. doi: 10.1080/09613218.2011.576849

HKU. (2019). Towards zero waste smart cities in the Greater Bay Area – Establishing a Waste Trade Organisation (WTO) for construction waste materials. Available at: https://www.hku.hk/press/news_detail_19281.html.

Ho, N. Y., Lee, Y. P. K., Lim, W. F., Zayed, T., Chew, K. C., Low, G. L., . . . Ting, S. K. (2013). Efficient utilization of recycled concrete aggregate in structural concrete. *Journal of Materials in Civil Engineering, 25*(3), 318-327. doi: 10.1061/(asce)mt.1943-5533.0000587

Hou, Y. Q., Ji, X. P., Zou, L., Liu, S., & Su, X. L. (2016). Performance of cement-stabilised crushed brick aggregates in asphalt pavement base and subbase applications. *Road Materials and Pavement Design, 17*(1), 120-135. doi: 10.1080/14680629.2015.1064466

Hu, M. M., van der Voet, E., & Huppes, G. (2010). Dynamic material flow analysis for strategic construction and demolition waste management in Beijing. *Journal of Industrial Ecology, 14*(3), 440-456. doi: 10.1111/j.1530-9290.2010.00245.x

Huang, S. L., & Hsu, W. L. (2003). Materials flow analysis and emergy evaluation of Taipei's urban construction. *Landscape and Urban Planning, 63*(2), 61-74. doi: 10.1016/s0169-2046(02)00152-4

Huang, S., Zhao, X., Sun, Y. Q., Ma, J. L., Gao, X. F., Xie, T., . . . Zhao, Y. C. (2016). Spatial distribution of organic pollutants in industrial construction and demolition waste and their mutual interaction on an abandoned pesticide manufacturing plant. *Environmental Science-Processes & Impacts, 18*(4), 482-492. doi: 10.1039/c6em00019c

—— (2017). Pollution of hazardous substances in industrial construction and demolition wastes and their multi-path risk within an abandoned pesticide manufacturing plant. *Frontiers of Environmental Science & Engineering, 11*(1), 13. doi: 10.1007/s11783-017-0901-2

Hunkeler, D. (2006). Societal LCA methodology and case study (12 pp.). *The International Journal of Life Cycle Assessment*, *11*(6), 371-382.

Hunkeler, D., & Rebitzer, G. (2005). The future of life cycle assessment. *The International Journal of Life Cycle Assessment*, *10*(5), 305-308.

Hutchins, M. J., & Sutherland, J. W. (2008). An exploration of measures of social sustainability and their application to supply chain decisions. *Journal of Cleaner Production*, *16*(15), 1688-1698.

Iden, S. C., Delay, M., Frimmel, F. H., & Durner, W. (2008). Assessing contaminant mobilization from waste materials: Application of Bayesian parameter estimation to batch extraction tests at varying liquid-to-solid ratios. *Environmental Science & Technology, 42*(10), 3717-3723. doi: 10.1021/es702171z

Jaillon, L., Poon, C. S., & Chiang, Y. H. (2009). Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management, 29*(1), 309-320. doi: 10.1016/j.wasman.2008.02.015

Jain, P., Powell, J., & Tolaymat, T. (2015). Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/111, 2015.

Jang, Y. C., & Townsend, T. G. (2001). Occurrence of organic pollutants in recovered soil fines from construction and demolition waste. *Waste Management, 21*(8), 703-715. doi: 10.1016/s0956-053x(01)00007-1

Johnson, C. A., Moench, H., & Brandenberger, S. (1999). Assessing the potential long-term behavior of the landfill fraction of sorted demolition wastes. *Journal of Environmental Quality, 28*(4), 1061-1067.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., . . . Rosenbaum, R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*, *8*(6), 324.

Jørgensen, A., Le Bocq, A., Nazarkina, L., & Hauschild, M. (2008). Methodologies for social life cycle assessment. *The International Journal of Life Cycle Assessment*, *13*(2), 96.

Jung, J. S., Song, S. H., Jun, M. H., & Park, S. S. (2015). A comparison of economic feasibility and emission of carbon dioxide for two recycling processes. *Ksce Journal of Civil Engineering, 19*(5), 1248-1255. doi: 10.1007/s12205-015-0708-2

Kalbe, U., Berger, W., Eckardt, J., & Simon, F. G. (2008). Evaluation of leaching and extraction procedures for soil and waste. *Waste Management, 28*(6), 1027-1038. doi: 10.1016/j.wasman.2007.03.008

Kanellopoulos, A., Nicolaides, D., & Petrou, M. F. (2014). Mechanical and durability properties of concretes containing recycled lime powder and recycled aggregates. *Construction and Building Materials, 53*, 253-259. doi: 10.1016/j.conbuildmat.2013.11.102

Karavezyris, V. (2007). Report: Treatment of commercial, construction and demolition waste in North Rhine-Westphalia: Policy-making and operation options. *Waste Management & Research, 25*(2), 183-189. doi: 10.1177/0734242x07075249

Kern, A. P., Dias, M. F., Kulakowski, M. P., & Gomes, L. P. (2015). Waste generated in high-rise buildings construction: A quantification model based on statistical multiple regression. *Waste Management, 39*, 35-44. doi: 10.1016/j.wasman.2015.01.043

Kim, Y., & Yang, G. (2002). A novel design for anaerobic chemical oxygen demand and nitrogen removal from leachate in a semiaerobic landfill. *Journal of the Air & Waste Management Association, 52*(10), 1139-1152.

Klang, A., Vikman, P. A., & Brattebo, H. (2003). Sustainable management of demolition waste -- an integrated model for the evaluation of environmental, economic and social aspects. *Resources Conservation and Recycling, 38*(4), 317-334. doi: 10.1016/s0921-3449(02)00167-2

Klöpffer, W., & Renner, I. (2008). Life cycle based sustainability assessment of products. In: *Environmental management accounting for cleaner production* (pp. 91-102). Springer, Dordrecht.

Koellner, T., Suh, S., Weber, O., Moser, C., & Scholz, R. W. (2007). Environmental impacts of conventional and sustainable investment funds compared using input-output life cycle assessment. *Journal of Industrial Ecology*, *11*(3), 41-60.

Kralj, D. (2009). Experimental study of recycling lightweight concrete with aggregates containing expanded glass. *Process Safety and Environmental Protection, 87*(4), 267-273. doi: 10.1016/j.psep.2009.03.003

Kruger, O., Kalbe, U., Berger, W., Simon, F. G., & Meza, S. L. (2012). Leaching experiments on the release of heavy metals and PAH from soil and waste materials. *Journal of Hazardous Materials, 207*, 51-55. doi: 10.1016/j.jhazmat.2011.02.016

Kucukvar, M., Egilmez, G., & Tatari, O. (2014). Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life cycle analysis. *Waste Management & Research, 32*(6), 500-508. doi: 10.1177/0734242x14536457

—— (2016). Life Cycle Assessment and Optimization-Based Decision Analysis of Construction Waste Recycling for a LEED-Certified University Building. *Sustainability, 8*(1), 13. doi: 10.3390/su8010089

Kumar, R. (2017). Influence of recycled coarse aggregate derived from construction and demolition waste (CDW) on abrasion resistance of pavement concrete. *Construction and Building Materials, 142*, 248-255. doi: 10.1016/j.conbuildmat.2017.03.077

Labuschagne, C., Brent, A. C., & Van Erck, R. P. (2005). Assessing the sustainability performance of industries. *Journal of Cleaner Production*, *13*(4), 373-385.

Lau, H. H., Whyte, A., & Law, P. L. (2008). Composition and characteristics of construction waste generated by residential housing project. *International Journal of Environmental Research, 2*(3), 261-268.

Lee, J. Y., Moon, S. H., Yi, M. J., & Yun, S. T. (2008). Groundwater contamination with petroleum hydrocarbons, chlorinated solvents and high pH: Implications for multiple sources. *Quarterly*

Journal of Engineering Geology and Hydrogeology, 41, 35-47. doi: 10.1144/1470-9236/07-021

Leite, F. D., Motta, R. D., Vasconcelos, K. L., & Bernucci, L. (2011). Laboratory evaluation of recycled construction and demolition waste for pavements. *Construction and Building Materials, 25*(6), 2972-2979. doi: 10.1016/j.conbuildmat.2010.11.105

Li, J. R., Ding, Z. K., Mi, X. M., & Wang, J. Y. (2013). A model for estimating construction waste generation index for building project in China. *Resources Conservation and Recycling, 74*, 20-26. doi: 10.1016/j.resconrec.2013.02.015

Li, J. X., & Yang, E. H. (2017). Macroscopic and microstructural properties of engineered cementitious composites incorporating recycled concrete fines. *Cement & Concrete Composites, 78*, 33-42. doi: 10.1016/j.cemconcomp.2016.12.013

Li, J., Wang, M.-H., & Ho, Y.-S. (2011). Trends in research on global climate change: A Science Citation Index Expanded-based analysis. *Global and Planetary Change, 77*(1-2), 13-20.

Li, S., Wu, H., & Ding, Z. (2018). Identifying sustainable wood sources for the construction industry: A case study. *Sustainability*, *10*(1), 139. doi: https://doi.org/10.3390/su10010139

Li, Z. D., Shen, G. Q., & Alshawi, M. (2014). Measuring the impact of prefabrication on construction waste reduction: An empirical study in China. *Resources Conservation and Recycling, 91*, 27-39. doi: 10.1016/j.resconrec.2014.07.013

Lippiatt, B. C. (2000). *BEES 2.0 Building for Environmental and Economic Sustainability: Technical Manual and User Guide* (No. NIST Interagency/Internal Report (NISTIR)-6520).

Lovato, P. S., Possan, E., Dal Molin, D. C. C., Masuero, A. B., & Ribeiro, J. L. D. (2012). Modeling of mechanical properties and durability of recycled aggregate concretes. *Construction and Building Materials, 26*(1), 437-447. doi: 10.1016/j.conbuildmat.2011.06.043

Lu, M., Lau, S. C., & Poon, C. S. (2009). Simulation approach to evaluating cost efficiency of selective demolition practices: Case of Hong Kong's Kai Tak Airport demolition. *Journal of Construction Engineering and Management, 135*(6), 448-457. doi: 10.1061/(asce)0733-9364(2009)135:6(448)

Lu, W. S., & Yuan, H. P. (2010). Exploring critical success factors for waste management in construction projects of China. *Resources Conservation and Recycling, 55*(2), 201-208. doi: 10.1016/j.resconrec.2010.09.010

Lu, W. S., Chen, X., Ho, D. C. W., & Wang, H. D. (2016). Analysis of the construction waste management performance in Hong Kong: The public and private sectors compared using big data. *Journal of Cleaner Production, 112*, 521-531. doi: 10.1016/j.jclepro.2015.06.106

Lu, W. S., Chen, X., Peng, Y., & Shen, L. Y. (2015). Benchmarking construction waste management performance using big data. *Resources Conservation and Recycling, 105*, 49-58. doi: 10.1016/j.resconrec.2015.10.013

Lu, W. S., Yuan, H. P., Li, J. R., Hao, J. J. L., Mi, X. M., & Ding, Z. K. (2011). An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Waste Management, 31*(4), 680-687. doi: 10.1016/j.wasman.2010.12.004

Lu, W., Webster, C., Peng, Y., Chen, X., & Zhang, X. (2017). Estimating and calibrating the amount of building-related construction and demolition waste in urban China. *International Journal of Construction Management,* 17(1), 13-24. doi: https://doi.org/10.1080/15623599.2016.1166548

Malia, M., de Brito, J., Pinheiro, M. D., & Bravo, M. (2013). Construction and demolition waste indicators. *Waste Management & Research, 31*(3), 241-255. doi: 10.1177/0734242x12471707

Manowong, E. (2012). Investigating factors influencing construction waste management efforts in developing countries: An experience from Thailand. *Waste Management & Research, 30*(1), 56-71. doi: 10.1177/0734242x10387012

Marrero, M., Puerto, M., Rivero-Camacho, C., Freire-Guerrero, A., & Solis-Guzman, J. (2017). Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land. *Resources Conservation and Recycling, 117*, 160-174. doi: 10.1016/j.resconrec.2016.10.020

Marzouk, M., & Azab, S. (2014). Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. *Resources Conservation and Recycling, 82*, 41-49. doi: 10.1016/j.resconrec.2013.10.015

Matias, D., de Brito, J., Rosa, A., & Pedro, D. (2013). Mechanical properties of concrete produced with recycled coarse aggregates -- Influence of the use of superplasticsizers. *Construction and Building Materials, 44*, 101-109. doi: 10.1016/j.conbuildmat.2013.03.011

McDougall, F. R., White, P. R., Franke, M., & Hindle, P. (2008). *Integrated solid waste management: a life cycle inventory*. John Wiley & Sons.

Mercader-Moyano, P., & Ramirez-de-Arellano-Agudo, A. (2013). Selective classification and quantification model of C&D waste from material resources consumed in residential building construction. *Waste Management & Research, 31*(5), 458-474. doi: 10.1177/0734242x13477719

Mercante, I. T., Bovea, M. D., Ibanez-Fores, V., & Arena, A. P. (2012). Life cycle assessment of construction and demolition waste management systems: A Spanish case study. *International Journal of Life Cycle Assessment, 17*(2), 232-241. doi: 10.1007/s11367-011-0350-2

Merino, M. D., Gracia, P. I., & Azevedo, I. S. W. (2010). Sustainable construction: Construction and demolition waste reconsidered. *Waste Management & Research, 28*(2), 118-129. doi: 10.1177/0734242x09103841

Miatto, A, Schandl, H & Tanikawa, H 2017, 'How important are realistic building lifespan assumptions for material stock and demolition waste accounts?', *Resources Conservation and Recycling*, vol. 122, Jul, pp. 143-154.

Mielnik, O., & Goldemberg, J. (2002). Foreign direct investment and decoupling between energy and gross domestic product in developing countries. *Energy Policy*, *30*(2), 87-89.

Miguélez, E., & Moreno, R. (2015). Knowledge flows and the absorptive capacity of regions. *Research Policy*, *44*(4), 833-848.

Miranda, L. F. R., Constantino, C. S., Monich, C. R., & Neto, A. A. D. (2013). Use of recycled sand produced at construction sites in bedding mortars. *Journal of Materials in Civil Engineering, 25*(2), 236-242. doi: 10.1061/(asce)mt.1943-5533.0000593

Miranda, L. F. R., Lapenda, M. P., Teixeira, S. H. C., & Vogt, V. (2014). Rational procedure for composition of screed mortar with recycled sand at a construction site. *Journal of Materials in Civil Engineering, 26*(5), 855-862. doi: 10.1061/(asce)mt.1943-5533.0000877

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: A comparative analysis. *Scientometrics*, *106*(1), 213-228.

Nassar, A. I., Mohammed, M. K., Thom, N., & Parry, T. (2016). Mechanical, durability and microstructure properties of cold asphalt emulsion mixtures with different types of filler. *Construction and Building Materials, 114*, 352-363. doi: 10.1016/j.conbuildmat.2016.03.112

Norris, G. A. (2006). Social impacts in product life cycles: Towards life cycle attribute assessment. *The International Journal of Life Cycle Assessment*, *11*(1), 97-104.

NSW-EPA, NSW Environment Protection Authority, (2019). Waste Avoidance and Resource Recovery Strategy Progress Report 2017--18, Available at: https://www.epa.nsw.gov.au/publications/wastestrategy/19p1690-warr-strategy-progress-report-2017-18.

Ortiz, O., Pasqualino, J. C., & Castells, F. (2010). Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. *Waste Management, 30*(4), 646-654. doi: 10.1016/j.wasman.2009.11.013

Osmani, M., Glass, J., & Price, A. D. (2008). Architects' perspectives on construction waste reduction by design. *Waste Management*, *28*(7), 1147-1158.

Oygard, J. K., Gjengedal, E., & Mage, A. (2005). Mass-balance estimation of heavy metals and selected anions at a landfill receiving MSWI bottom ash and mixed construction wastes. *Journal of Hazardous Materials, 123*(1-3), 70-75. doi: 10.1016/j.jhazmat.2005.04.022

Park, J., & Tucker, R. (2017). Overcoming barriers to the reuse of construction waste material in Australia: A review of the literature. *International Journal of Construction Management,* 17(3), 228-237. doi: https://doi.org/10.1080/15623599.2016.1192248

Pasandin, A. R., & Perez, I. (2013). Laboratory evaluation of hot-mix asphalt containing construction and demolition waste. *Construction and Building Materials, 43*, 497-505. doi: 10.1016/j.conbuildmat.2013.02.052

Penacho, P., de Brito, J., & Veiga, M. R. (2014). Physico-mechanical and performance characterization of mortars incorporating fine glass waste aggregate. *Cement & Concrete Composites, 50*, 47-59. doi: 10.1016/j.cemconcomp.2014.02.007

Penteado, C. S. G., & Rosado, L. P. (2016). Comparison of scenarios for the integrated management of construction and demolition waste by life cycle assessment: A case study in Brazil. *Waste Management & Research, 34*(10), 1026-1035. doi: 10.1177/0734242x16657605

Poon, C. S., & Chan, D. X. (2006). Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction and Building Materials, 20*(8), 578-585. doi: 10.1016/j.cpnbuildmat.2005.01.045

Poon, C. S., Ann, T. W., & Ng, L. H. (2001). Onsite sorting of construction and demolition waste in Hong Kong. *Resources, Conservation and Recycling*, *32*(2), 157-172

Poon, C. S., Yu, A. T. W., Wong, A., & Yip, R. (2013). Quantifying the impact of construction waste charging scheme on construction waste management in Hong Kong. *Journal of Construction Engineering and Management-Asce, 139*(5), 466-479. doi: 10.1061/(asce)co.1943-7862.0000631

Poon, C. S., Yu, A. T., & Jaillon, L. (2004). Reducing building waste at construction sites in Hong Kong. *Construction Management and Economics*, *22*(5), 461-470

Prell, C. (2012). *Social network analysis: history, theory and methodology*: Sage.

Pritchard, A. (1969). Statistical bibliography or bibliometrics. *Journal of Documentation, 25*(4), 348-349.

QG, Queensland Government, (2018). Recycling and Waste in Queensland 2018 report. Available at: https://www.qld.gov.au/environment/pollution/management/waste/recovery/data-reports/recycling-waste

QG, Queensland Government, (2019). Transforming Queensland's Recycling and Waste Industry Directions Paper. Available at: https://www.qld.gov.au/__data/assets/pdf_file/0021/69060/transforming-qlds-recycling-waste-industry-directions-paper.pdf

Qudrat-Ullah, H., & Seong, B. S. (2010). How to do structural validity of a system dynamics type simulation model: The case of an energy policy model. *Energy Policy*, *38*(5), 2216-2224.

Rafi, M. M., Qadir, A., Ali, S., & Siddiqui, S. H. (2014). Performance of hot mix asphalt mixtures made of recycled aggregates. *Journal of Testing and Evaluation, 42*(2), 357-367. doi: 10.1520/jte20130004

Randolph, J. J. (2009). A guide to writing the dissertation literature review. *Practical Assessment, Research & Evaluation*, *14*(13), 1-13.

Rivero, A. J., Sathre, R., & Navarro, J. G. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources Conservation and Recycling, 108*, 171-181. doi: 10.1016/j.resconrec.2016.01.014

Rodriguez-Robles, D., Garcia-Gonzalez, J., Juan-Valdes, A., Moran-del Pozo, J. M., & Guerra-Romero, M. I. (2015). Overview regarding construction and demolition waste in Spain. *Environmental Technology, 36*(23), 3060-3070. doi: 10.1080/09593330.2014.957247

Roussat, N., Mehu, J., & Dujet, C. (2009). Indicators to assess the recovery of natural resources contained in demolition waste. *Waste Management & Research, 27*(2), 159-166. doi: 10.1177/0734242x08089839

Roussat, N., Mehu, J., Abdelghafour, M., & Brula, P. (2008). Leaching behaviour of hazardous demolition waste. *Waste Management, 28*(11), 2032-2040. doi: 10.1016/j.wasman.2007.10.019

Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. *Clean Technologies and Environmental Policy*, *16*(2), 329-339.

Saarivirta, T., & Consoli, D. (2014). Where did they go? A study on newly established universities and graduate mobility in Finland. In: The economics of knowledge generation and distribution (pp. 92-116): Routledge.

Saez, P. V., Merino, M. D., Gonzalez, A. S., & Porras-Amores, C. (2013). Best practice measures assessment for construction and demolition waste management in building constructions. *Resources Conservation and Recycling, 75*, 52-62. doi: 10.1016/j.resconrec.2013.03.009

Shen, L. Y., Tam, V. W. Y., & Li, C. Y. (2009). Benefit analysis on replacing in situ concreting with precast slabs for temporary construction works in pursuing sustainable construction practice. *Resources Conservation and Recycling, 53*(3), 145-148. doi: 10.1016/j.resconrec.2008.11.001

Shen, L. Y., Tam, V. W., Tam, C. M., & Drew, D. (2004). Mapping approach for examining waste management on construction sites. *Journal of Construction Engineering and Management*, *130*(4), 472-481.

Shin, E., & Kang, J. (2015). Migration of calcium hydroxide compounds in construction waste soil. *Advances in Environmental Research-an International Journal, 4*(3), 183-196. doi: 10.12989/aer.2015.4.3.183

Shin, W. S., Na, K. R., & Kim, Y. K. (2016). Adsorption of metal ions from aqueous solution by recycled aggregate: Estimation of pretreatment effect. *Desalination and Water Treatment, 57*(20), 9366-9374. doi: 10.1080/19443994.2015.1029528

Silva, R. V., de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials, 65*, 201-217. doi: https://doi.org/10.1016/j.conbuildmat.2014.04.117

—— (2015a). Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete. *Engineering Structures, 100*, 31-42. doi: https://doi.org/10.1016/j.engstruct.2015.06.004

—— (2015b). Tensile strength behaviour of recycled aggregate concrete. *Construction and Building Materials, 83*, 108-118. doi: 10.1016/j.conbuildmat.2015.03.034

Sim, J., & Park, C. (2011). Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. *Waste Management, 31*(11), 2352-2360. doi: 10.1016/j.wasman.2011.06.014

Simion, I. M., Ghinea, C., Maxineasa, S. G., Taranu, N., Bonoli, A., & Gavrilescu, M. (2013). Ecological footprint applied in the assessment of construction and demolition waste integrated management. *Environmental Engineering and Management Journal, 12*(4), 779-788.

Singh, J. (2008). Distributed R&D, cross-regional knowledge integration and quality of innovative output. *Research Policy*, *37*(1), 77-96.

Solis-Guzman, J., Marrero, M., Montes, M. V., & Ramirez-De-Arellano, A. (2009). A Spanish model for quantification and management of construction waste. *Waste Management, 29*(9), 2542-2548. doi: 10.1016/j.wasman.2009.05.009

Song, J., Almeida, P., & Wu, G. (2003). Learning-by-hiring: When is mobility more likely to facilitate interfirm knowledge transfer? *Management Science*, *49*(4), 351-365.

Sou, W. I., Chu, A., & Chiueh, P. T. (2016). Sustainability assessment and prioritisation of bottom ash management in Macao. *Waste Management & Research, 34*(12), 1275-1282. doi: 10.1177/0734242x16665914

Soutsos, M., & Fulton, M. C. (2016). Recycling of demolition waste in Merseyside. *Proceedings of the Institution of Civil Engineers-Construction Materials, 169*(2), 54-66. doi: 10.1680/coma.15.00012

Spoerri, A., Lang, D. J., Binder, C. R., & Scholz, R. W. (2009). Expert-based scenarios for strategic waste and resource management planning: C&D waste recycling in the Canton of Zurich, Switzerland. *Resources Conservation and Recycling, 53*(10), 592-600. doi: 10.1016/j.resconrec.2009.04.011

Srour, I. M., Chehab, G. R., El-Fadel, M., & Tamraz, S. (2013). Pilot-based assessment of the economics of recycling construction demolition waste. *Waste Management & Research, 31*(11), 1170-1179. doi: 10.1177/0734242x13479430

Steen, B. (1999). A systematic approach to environmental priority strategies in product development (EPS): version 2000-models and data of the default method (p. 67). Gothenburg, Sweden: Centre for Environmental Assessment of Products and Material Systems.

Stefanidou, M., Anastasiou, E., & Filikas, K. G. (2014). Recycled sand in lime-based mortars. *Waste Management, 34*(12), 2595-2602. doi: 10.1016/j.wasman.2014.09.005

Stenis, J. (2005). Construction waste management based on industrial management models: A Swedish case study. *Waste Management & Research, 23*(1), 13-19. doi: 10.1177/0734242x05050184

Stephan, A., & Athanassiadis, A. (2018). Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. *Resources, Conservation and Recycling*, *129*, 248-262. doi: https://doi.org/10.1016/j.resconrec.2017.09.022

Stocker, T. F., Qin, D., Plattner, G., Tignor, M., Allen, S. K., Boschung, J., ... Midgley, P. M. (2013). IPCC, 2013: Summary for policymakers in climate change 2013: The physical science basis, contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press.

Sutton, P. C., Elvidge, C. D., & Ghosh, T. (2007). Estimation of gross domestic product at sub-national scales using nighttime satellite imagery. *International Journal of Ecological Economics & Statistics*, *8*(S07), 5-21.

SV, Sustainability Victoria, (2017). Victorian Recycling industry Annual Report 2015 – 2016. Available at: https://www.sustainability.vic.gov.au/About-us/Publications/Waste-VRIAR-2015-2016

SV, Sustainability Victoria, (2018a). State-wide Waste and Resource Recovery Infrastructure Plan (Victoria 2017). Available at: https://www.sustainability.vic.gov.au/about-us/what-we-do/strategy-and-planning/statewide-waste-and-resource-recovery-infrastructure-plan

SV, Sustainability Victoria, (2018b). Victorian Recycling industry Annual Report 2016 – 2017. Available at: https://www.sustainability.vic.gov.au/About-us/Publications/Waste-VRIAR-2016-2017

Tam, V. W. Y. (2008). On the effectiveness in implementing a waste-management-plan method in construction. *Waste Management, 28*(6), 1072-1080. doi: 10.1016/j.wasman.2007.04.007

Tam, V. W. Y., & Hao, J. J. L. (2016). Attitudes towards recycling on construction sites. *Proceedings of the Institution of Civil Engineers--Waste and Resource Management, 169*(3), 6. doi: 10.1680/jwarm.15.00006

Tam, V. W. Y., & Tam, C. M. (2009). Parameters for assessing recycled aggregate and their correlation. *Waste Management & Research, 27*(1), 52-58. doi: 10.1177/0734242x07079875

Tam, V. W. Y., Fung, I. W. H., Sing, M. C. P., & Ogunlana, S. O. (2015). Best practice of prefabrication implementation in the Hong Kong public and private sectors. *Journal of Cleaner Production, 109*, 216-231. doi: 10.1016/j.jclepro.2014.09.045

Tam, V. W. Y., Kotrayothar, D., & Xiao, J. Z. (2015). Long-term deformation behaviour of recycled aggregate concrete. *Construction and Building Materials, 100*, 262-272. doi: 10.1016/j.conbuildmat.2015.10.013

Tam, V. W. Y., Li, J. R., & Cai, H. (2014). System dynamic modeling on construction waste management in Shenzhen, China. *Waste Management & Research, 32*(5), 441-453. doi: 10.1177/0734242x14527636

Tam, V. W. Y., Tam, C. M., & Le, K. N. (2007). Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. *Resources Conservation and Recycling, 50*(1), 82-101. doi: 10.1016/j.resconrec.2006.05.012

—— (2010). Cross-cultural comparison of concrete recycling decision-making and implementation in construction industry. *Waste Management, 30*(2), 291-297. doi: 10.1016/j.wasman.2009.09.044

Tam, V. W., & Tam, C. M. (2008). Waste reduction through incentives: A case study. *Building Research and Information, 36*(1), 37-43. doi: 10.1080/09613210701417003

Tam, V. W., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials*, 172, 272-292.

Udawatta, N., Zuo, J., Chiveralls, K., & Zillante, G. (2015a). Attitudinal and behavioural approaches to improving waste management on construction projects in Australia: Benefits and limitations. *International Journal of Construction Management, 15*(2), 137-147. doi: 10.1080/15623599.2015.1033815

—— (2015b). Improving waste management in construction projects: An Australian study. *Resources Conservation and Recycling, 101*, 73-83. doi: 10.1016/j.resconrec.2015.05.003

Ulsen, C., Kahn, H., Hawlitschek, G., Masini, E. A., Angulo, S. C., & John, V. M. (2013). Production of recycled sand from construction and demolition waste. *Construction and Building Materials, 40*, 1168-1173. doi: 10.1016/j.conbuildmat.2012.02.004

Van Praagh, M., & Modin, H. (2016). Leaching of chloride, sulphate, heavy metals, dissolved organic carbon and phenolic organic pesticides from contaminated concrete. *Waste Management, 56*, 352-358. doi: 10.1016/j.wasman.2016.07.009

van Raan, A. F. (2005). For your citations only? Hot topics in bibliometric analysis. *Measurement: Interdisciplinary Research and Perspectives, 3*(1), 50-62.

Vegas, I., Broos, K., Nielsen, P., Lambertz, O., & Lisbona, A. (2015). Upgrading the quality of mixed recycled aggregates from construction and demolition waste by using near-infrared sorting technology. *Construction and Building Materials, 75*, 121-128. doi: 10.1016/j.conbuildmat.2014.09.109

Vieira, T., Alves, A., de Brito, J., Correia, J. R., & Silva, R. V. (2016). Durability-related performance of concrete containing fine recycled aggregates from crushed bricks and sanitary ware. *Materials & Design, 90*, 767-776. doi: 10.1016/j.matdes.2015.11.023

Vitale, P., Arena, N., Di Gregorio, F., & Arena, U. (2017). Life cycle assessment of the end-of-life phase of a residential building. *Waste Management, 60*, 311-321. doi: 10.1016/j.wasman.2016.10.002

Wackernagel, M. (1994). *Ecological footprint and appropriated carrying capacity: a tool for planning toward sustainability* (Doctoral dissertation, University of British Columbia).

Wang, J. Y., Li, Z. D., & Tam, V. W. Y. (2014). Critical factors in effective construction waste minimization at the design stage: A Shenzhen case study, China. *Resources Conservation and Recycling, 82*, 1-7. doi: 10.1016/j.resconrec.2013.11.003

Wang, J. Y., Touran, A., Christoforou, C., & Fadlalla, H. (2004). A systems analysis tool for construction and demolition waste management. *Waste Management, 24*(10), 989-997. doi: 10.1016/j.wasman.2004.07.010

Wang, J. Y., Yuan, H. P., Kang, X. P., & Lu, W. S. (2010). Critical success factors for onsite sorting of construction waste: A china study. *Resources Conservation and Recycling, 54*(11), 931-936. doi: 10.1016/j.resconrec.2010.01.012

Wang, J., Wu, H., Duan, H., Zillante, G., Zuo, J., & Yuan, H. (2018). Combining life cycle assessment and building information modelling to account for carbon emission of building demolition waste: A case study. *Journal of Cleaner Production, 172*, 3154-3166.

Wang, J., Wu, H., Tam, V. W., & Zuo, J. (2019). Considering life-cycle environmental impacts and society's willingness for optimizing construction and demolition waste management fee: An empirical study of China. *Journal of Cleaner Production*, 206, 1004-1014.

Wang, Y., Lai, N., Zuo, J., Chen, G., & Du, H. (2016). Characteristics and trends of research on waste-to-energy incineration: A bibliometric analysis, 1999–2015. *Renewable and Sustainable Energy Reviews, 66*, 95-104. doi: https://doi.org/10.1016/j.rser.2016.07.006

Warren, J. D., Chong, W. K., & Kim, C. (2007). Recycling construction and demolition waste for construction in Kansas City metropolitan area, Kansas and Missouri. *Transportation Research Record* (2011), 193-200. doi: 10.3141/2011-21

Waste Authority WA, (2018). Recycling activity in Western Australia 2016 – 2017. Available at: https://www.wasteauthority.wa.gov.au/media/files/documents/Recycling_Activity_in_Western_Australia_2016-17.pdf

Webster, J., & Watson, R. T. (2002). Analyzing the past to prepare for the future: Writing a literature review. *MIS Quarterly*, 13-23.

Wehrer, M., & Totsche, K. U. (2008). Effective rates of heavy metal release from alkaline wastes -- Quantified by column outflow experiments and inverse simulations. *Journal of Contaminant Hydrology, 101*(1-4), 53-66. doi: 10.1016/j.jconhyd.2008.07.005

Weidema, B. P. (2006). The integration of economic and social aspects in life cycle impact assessment. *The International Journal of Life Cycle Assessment*, *11*(1), 89-96.

Wiedenhofer, D., Steinberger, J. K., Eisenmenger, N., & Haas, W. (2015). Maintenance and expansion modeling material stocks and flows for residential buildings and transportation networks in the EU25. *Journal of Industrial Ecology, 19*(4), 538-551. doi: 10.1111/jiec.12216

Won, J., Cheng, J. C. P., & Lee, G. (2016). Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea. *Waste Management, 49*, 170-180. doi: 10.1016/j.wasman.2015.12.026

Wu, H., Duan, H., Wang, J., Wang, T., & Wang, X. (2015). Quantification of carbon emission of construction waste by using streamlined LCA: A case study of Shenzhen, China. *Journal of Material Cycles and Waste Management, 17*(4), 637-645. doi: 10.1007/s10163-015-0404-9

Wu, H., Duan, H., Zheng, ., Wang, J., Niu, Y., & Zhang, G. (2016). Demolition waste generation and recycling potentials in a rapidly developing flagship megacity of South China: Prospective scenarios and implications. *Construction and Building Materials, 113*, 1007-1016. doi: 10.1016/j.conbuildmat.2016.03.130

Wu, H., Wang, J, Duan, H., Ouyang, L., Huang, W., & Zuo, J. (2016). An innovative approach to managing demolition waste via GIS (geographic information system): A case study in Shenzhen city, China. *Journal of Cleaner Production, 112*, 494-503. doi: 10.1016/j.jclepro.2015.08.096

Wu, H., Yuan, H., Wang, J., Ouyang, L., & Li, Z. (2017). An investigation of demolition waste management: Case of Shenzhen in China. In: *Proceedings* of the 20th International Symposium on Advancement of Construction Management and Real Estate (pp. 1157-1167). Singapore: Springer.

Wu, H., Zuo, J., Zillante, G., Wang, J., & Yuan, H. (2019a). Status quo and future directions of construction and demolition waste research: A critical review. *Journal of Cleaner Production*, 118163.

Wu, H., Zuo, J., Yuan, H., Zillante, G., & Wang, J. (2019b). A review of performance assessment methods for construction and demolition waste management. *Resources, Conservation and Recycling*, 150, 104407.

Wu, Z. Z., Yu, A. T. W., & Shen, L. Y. (2017). Investigating the determinants of contractor's construction and demolition waste management behavior in Mainland China. *Waste Management, 60*, 290-300. doi: 10.1016/j.wasman.2016.09.001

Xuan, D. X., Molenaar, A. A. A., & Houben, L. J. M. (2016). Shrinkage cracking of cement treated demolition waste as a road base. *Materials and Structures, 49*(1-2), 631-640. doi: 10.1617/s11527-015-0524-7

Xue, C. Z., Shen, A. Q., Guo, Y. C., & He, T. Q. (2016). Utilization of construction waste composite powder materials as cementitious materials in small-scale prefabricated concrete. *Advances in Materials Science and Engineering*, 1-11. doi: 10.1155/2016/8947935

Ye, G., Yuan, H. P., Shen, L. Y., & Wang, H. X. (2012). Simulating effects of management measures on the improvement of the environmental performance of construction waste management. *Resources Conservation and Recycling, 62*, 56-63. doi: 10.1016/j.resconrec.2012.01.010

Yeheyis, M., Hewage, K., Alam, M. S., Eskicioglu, C., & Sadiq, R. (2013). An overview of construction and demolition waste management in Canada: A life cycle analysis approach to sustainability. *Clean Technologies and Environmental Policy, 15*(1), 81-91. doi: 10.1007/s10098-012-0481-6

Yu, A. T. W., Poon, C. S., Wong, A., Yip, R., & Jaillon, L. (2013). Impact of construction waste disposal charging scheme on work practices at construction sites in Hong Kong. *Waste Management, 33*(1), 138-146. doi: 10.1016/j.wasman.2012.09.023

Yuan, F., Shen, L. Y., & Li, Q. M. (2011). Emergy analysis of the recycling options for construction and demolition waste. *Waste Management, 31*(12), 2503-2511. doi: 10.1016/j.wasman.2011.07.001

Yuan, H. (2012). A model for evaluating the social performance of construction waste management. *Waste Management, 32*(6), 1218-1228. doi: 10.1016/j.wasman.2012.01.028

—— (2013). Key indicators for assessing the effectiveness of waste management in construction projects. *Ecological Indicators, 24*, 476-484. doi: 10.1016/j.ecolind.2012.07.022

Yuan, H., & Wang, J. (2014). A system dynamics model for determining the waste disposal charging fee in construction. *European Journal of Operational Research, 237*(3), 988-996. doi: 10.1016/j.ejor.2014.02.034

Yuan, H., & Shen, L. (2011). Trend of the research on construction and demolition waste management. *Waste Management, 31*(4), 670-679. doi: https://doi.org/10.1016/j.wasman.2010.10.030

Yuan, H., Wu, H., & Zuo, J. (2018). Understanding factors influencing project managers' behavioral intentions to reduce waste in construction projects. *Journal of Management in Engineering, 34*(6), 04018031.

Zamagni, A., Guinée, J., Heijungs, R., Masoni, P., & Raggi, A. (2012). Lights and shadows in consequential LCA. *The International Journal of Life Cycle Assessment*, *17*(7), 904-918.

Zambrana-Vasquez, D., Zabalza-Bribian, I., Janez, A., & Aranda-Uson, A. (2016). Analysis of the environmental performance of life cycle building waste management strategies in tertiary buildings. *Journal of Cleaner Production, 130*, 143-154. doi: 10.1016/j.jclepro.2016.02.048

Zega, C. J., Villagran-Zaccardi, Y. A., & Di Maio, A. A. (2010). Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. *Materials and Structures, 43*(1-2), 195-202. doi: 10.1617/s11527-009-9480-4

Zhao, W., Leeftink, R. B., & Rotter, V. S. (2010). Evaluation of the economic feasibility for the recycling of construction and demolition waste in China: The case of Chongqing. *Resources Conservation and Recycling, 54*(6), 377-389. doi: 10.1016/j.resconrec.2009.09.003

Zhao, W., Ren, H., & Rotter, V. S. (2011). A system dynamics model for evaluating the alternative of type in construction and demolition waste recycling center: The case of Chongqing, China. *Resources Conservation and Recycling, 55*(11), 933-944. doi: 10.1016/j.resconrec.2011.04.011

Zheng, L. N., Wu, H. Y., Zhang, H., Duan, H. B., Wang, J. Y., Jiang, W. P., . . . Song, Q. B. (2017). Characterizing the generation and flows of construction and demolition waste in China. *Construction and Building Materials, 136*, 405-413. doi: 10.1016/j.conbuildmat.2017.01.055.

Zopounidis, C., & Doumpos, M. (2002). Multicriteria classification and sorting methods: A literature review. *European Journal of Operational Research*, *138*(2), 229-246.

Appendix A: Ethics approval letter

THE UNIVERSITY of ADELAIDE

RESEARCH SERVICES
OFFICE OF RESEARCH ETHICS, COMPLIANCE AND INTEGRITY
THE UNIVERSITY OF ADELAIDE

LEVEL 4, RUNDLE MALL PLAZA
50 RUNDLE MALL
ADELAIDE SA 5000 AUSTRALIA

TELEPHONE +61 8 8313 5137
FACSIMILE +61 8 8313 3700
EMAIL hrec@adelaide.edu.au

CRICOS Provider Number 00123M

Our reference 33269

06 November 2018

Associate Professor Jian Zuo
School of Architecture & Built Environment

Dear Associate Professor Zuo

ETHICS APPROVAL No:	H-2018-244
PROJECT TITLE:	The impacts of cross-regional mobility of construction and demolition (C&D) waste on Australia

The ethics application for the above project has been reviewed by the Low Risk Human Research Ethics Review Group (Faculty of Arts and Faculty of the Professions) and is deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research (2007)* involving no more than low risk for research participants.

You are authorised to commence your research on:	06/11/2018
The ethics expiry date for this project is:	30/11/2021

NAMED INVESTIGATORS:

Chief Investigator:	Associate Professor Jian Zuo
Student - Postgraduate Doctorate by Research (PhD):	Mr Huanyu Wu
Associate Investigator:	Professor George Zillante
Associate Investigator:	Jiayuan Wang

CONDITIONS OF APPROVAL: Thank you for your responses to the matters raised. The revised application provided on 06/11/18 has been approved.

Ethics approval is granted for three years and is subject to satisfactory annual reporting. The form titled Annual Report on Project Status is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/research-services/oreci/human/reporting/. Prior to expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the information sheet and the signed consent form to retain. It is also a condition of approval that you immediately report anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,
- previously unforeseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol or project investigators; and
- the project is discontinued before the expected date of completion.

Yours sincerely,

Dr Anna Olijnyk

Convenor

Dr Jungho Suh
Convenor
The University of Adelaide

Appendix B: Supplementary tables

Table A-2.1 Reviewed C&D waste-related research articles

No.	Reviewed Paper
1	Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Owolabi, H. A., Alaka, H. A., & Kadiri, K. O. (2016). Reducing waste to landfill: A need for cultural change in the UK construction industry. *Journal of Building Engineering, 5*, 185-193. doi: 10.1016/j.jobe.2015.12.007
2	Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. *Resources Conservation and Recycling, 102*, 101-112. doi: 10.1016/j.resconrec.2015.06.001
3	Al-Sari, M. I., Al-Khatib, I. A., Avraamides, M., & Fatta-Kassinos, D. (2012). A study on the attitudes and behavioural influence of construction waste management in occupied Palestinian territory. *Waste Management & Research, 30*(2), 122-136. doi: 10.1177/0734242x11423066
4	Anastasiou, E., Filikas, K. G., & Stefanidou, M. (2014). Utilization of fine recycled aggregates in concrete with fly-ash and steel slag. *Construction and Building Materials, 50*, 154-161. doi: 10.1016/j.conbuildmat.2013.09.037
5	Arulrajah, A., Ali, M. M. Y., Disfani, M. M., & Horpibulsuk, S. (2014). Recycled-Glass Blends in Pavement Base/Subbase Applications: Laboratory and Field Evaluation. *Journal of Materials in Civil Engineering, 26*(7), 12. doi: 10.1061/(asce)mt.1943-5533.0000966
6	Arulrajah, A., Piratheepan, J., Disfani, M. M., & Bo, M. W. (2013). Geotechnical and Geoenvironmental Properties of Recycled Construction and Demolition Materials in Pavement Subbase Applications. *Journal of Materials in Civil Engineering, 25*(8), 1077-1088. doi: 10.1061/(asce)mt.1943-5533.0000652
7	Baldwin, A. N., Shen, L. Y., Poon, C. S., Austin, S. A., & Wong, I. (2008). Modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings. *Automation in Construction, 17*(3), 333-341. doi: 10.1016/j.autcon.2007.05.013
8	Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2006). A benefit-cost analysis on the economic feasibility of construction waste minimisation: The case of Malaysia. *Resources Conservation and Recycling, 48*(1), 86-98. doi: 10.1016/j.resconrec.2006.01.004
9	Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2007). Implementation of waste management and minimisation in the construction industry of Malaysia. *Resources Conservation and Recycling, 51*(1), 190-202. doi: 10.1016/j.resconrec.2006.09.004
10	Belagraa, L., Beddar, M., & Bouzid, A. (2017). Mabble fillers effect on the mechanical performance of a recycled aggregate concrete. *Environmental Engineering and Management Journal, 16*(1), 197-204.
11	Bergersen, O., & Haarstad, K. (2014). Treating landfill gas hydrogen sulphide with mineral wool waste (MWW) and rod mill waste (RMW). *Waste Management, 34*(1), 141-147. doi: 10.1016/j.wasman.2013.09.012
12	Bergsdal, H., Bohne, R. A., & Brattebo, H. (2007). Projection of construction and demolition waste in Norway. *Journal of Industrial Ecology, 11*(3), 27-39. doi: 10.1162/jiec.2007.1149

13	Bergsdal, H., Brattebo, H., Bohne, R. A., & Mueller, D. B. (2007). Dynamic material flow analysis for Norway's dwelling stock. *Building Research and Information, 35*(5), 557-570. doi: 10.1080/09613210701287588
14	Bernardo, M., Gomes, M. C., & de Brito, J. (2016). Demolition waste generation for development of a regional management chain model. *Waste Management, 49*, 156-169. doi: 10.1016/j.wasman.2015.12.027
15	Bilal, M., Oyedele, L. O., Akinade, O. O., Ajayi, S. O., Alaka, H. A., Owolabi, H. A., . . . Bello, S. A. (2016). Big data architecture for construction waste analytics (CWA): A conceptual framework. *Journal of Building Engineering, 6*, 144-156. doi: 10.1016/j.jobc.2016.03.002
16	Bjegovic, D., Stirmer, N., & Serdar, M. (2012). Durability properties of concrete with blended cements. *Materials and Corrosion-Werkstoffe Und Korrosion, 63*(12), 1087-1096. doi: 10.1002/maco.201206699
17	Blengini, G. A. (2009). Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. *Building and Environment, 44*(2), 319-330.
18	Blengini, G. A., & Garbarino, E. (2010). Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. *Journal of Cleaner Production, 18*(10-11), 1021-1030. doi: 10.1016/j.jclepro.2010.01.027
19	Bravo, M., de Brito, J., Pontes, J., & Evangelista, L. (2015). Durability performance of concrete with recycled aggregates from construction and demolition waste plants. *Construction and Building Materials, 77*, 357-369. doi: 10.1016/j.conbuildmat.2014.12.103
20	Cabalar, A. F., Abdulnafaa, M. D., & Karabash, Z. (2016). Influences of various construction and demolition materials on the behavior of a clay. *Environmental Earth Sciences, 75*(9), 9. doi: 10.1007/s12665-016-5631-4
21	Cheng, J. C., & Ma, L. Y. (2013). A BIM-based system for demolition and renovation waste estimation and planning. Waste management, 33(6), 1539-1551.
22	Choudhary, A., Shah, V., & Bishnoi, S. (2016). Effect of low cost fillers on cement hydration. *Construction and Building Materials, 124*, 533-543. doi: 10.1016/j.conbuildmat.2016.07.088
23	Cochran, K., Townsend, T., Reinhart, D., & Heck, H. (2007). Estimation of regional building-related C&D debris generation and composition: Case study for Florida, US. *Waste Management, 27*(7), 921-931. doi: 10.1016/j.wasman.2006.03.023
24	Coelho, A., & de Brito, J. (2011). Generation of construction and demolition waste in Portugal. *Waste Management & Research, 29*(7), 739-750. doi: 10.1177/0734242x11402253
25	Coelho, A., & de Brito, J. (2013). Economic viability analysis of a construction and demolition waste recycling plant in Portugal - part I: location, materials, technology and economic analysis. *Journal of Cleaner Production, 39*, 338-352. doi: 10.1016/j.jclepro.2012.08.024
26	Corinaldesi, V., & Moriconi, G. (2009). Behaviour of cementitious mortars containing different kinds of recycled aggregate. *Construction and Building Materials, 23*(1), 289-294. doi: 10.1016/j.conbuildmat.2007.12.006
27	Correia, J. R., de Brito, J., & Pereira, A. S. (2006). Effects on concrete durability of using recycled ceramic aggregates. *Materials and Structures, 39*(2), 169-177. doi: 10.1617/s11527-005-9014-7

28	da Silva, V. M., Gois, L. C., Duarte, J. B., da Silva, J. B., & Acchar, W. (2014). Incorporation of Ceramic Waste into Binary and Ternary Soil-Cement Formulations for the Production of Solid Bricks. *Materials Research-Ibero-American Journal of Materials, 17*(2), 326-331. doi: 10.1590/s1516-14392014005000014
29	Dantas, A. T. A., Leite, M. B., & Nagahama, K. D. (2013). Prediction of compressive strength of concrete containing construction and demolition waste using artificial neural networks. *Construction and Building Materials, 38*, 717-722. doi: 10.1016/j.conbuildmat.2012.09.026
30	Delay, M., Lager, T., Schulz, H. D., & Frimmel, F. H. (2007). Comparison of leaching tests to determine and quantify the release of inorganic contaminants in demolition waste. *Waste Management, 27*(2), 248-255. doi: 10.1016/j.wasman.2006.01.013
31	Denyes, M. J., Parisien, M. A., Rutter, A., & Zeeb, B. A. (2014). Physical, Chemical and Biological Characterization of Six Biochars Produced for the Remediation of Contaminated Sites. *Jove-Journal of Visualized Experiments,* (93), 1-12. doi: 10.3791/52183
32	Diyamandoglu, V., & Fortuna, L. M. (2015). Deconstruction of wood-framed houses: Material recovery and environmental impact. *Resources Conservation and Recycling, 100*, 21-30. doi: 10.1016/j.resconrec.2015.04.006
33	Dosho, Y. (2007). Development of a sustainable concrete waste recycling system - Application of recycled aggregate concrete produced by aggregate replacing method. *Journal of Advanced Concrete Technology, 5*(1), 27-42. doi: 10.3151/jact.5.27
34	Duan, H., Yu, D. F., Zuo, J., Yang, B., Zhang, Y. K., & Niu, Y. N. (2016). Characterization of brominated flame retardants in construction and demolition waste components: HBCD and PBDEs. *Science of the Total Environment, 572*, 77-85. doi: 10.1016/j.scitotenv.2016.07.165
35	Duran, X., Lenihan, H., & O'Regan, B. (2006). A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland. *Resources Conservation and Recycling, 46*(3), 302-320. doi: 10.1016/j.resconrec.2005.08.003
36	Engelsen, C. J., van der Sloot, H. A., & Petkovic, G. (2017). Long-term leaching from recycled concrete aggregates applied as sub-base material in road construction. *Science of the Total Environment, 587*, 94-101. doi: 10.1016/j.scitotenv.2017.02.052
37	Esa, M. R., Halog, A., & Rigamonti, L. (2017). Strategies for minimizing construction and demolition wastes in Malaysia. *Resources Conservation and Recycling, 120*, 219-229. doi: 10.1016/j.resconrec.2016,12.014
38	Esin, T., & Cosgun, N. (2007). A study conducted to reduce construction waste generation in Turkey. *Building and Environment, 42*(4), 1667-1674. doi: 10.1016/j.buildenv.2006.02.008
39	Evangelista, L., & de Brito, J. (2017). Flexural behaviour of reinforced concrete beams made with fine recycled concrete aggregates. *Ksce Journal of Civil Engineering, 21*(1), 353-363. doi: 10.1007/s12205-016-0653-8
40	Ferguson, D. W., & Male, J. W. (1980). The water-polltion potential from demolition waste-disposal. *Journal of Environmental Science and Health Part a-Environmental Science and Engineering, 15*(6), 545-559.

41	Galvin, A. P., Ayuso, J., Jimenez, J. R., & Agrela, F. (2012). Comparison of batch leaching tests and influence of pH on the release of metals from construction and demolition wastes. *Waste Management, 32*(1), 88-95. doi: 10.1016/j.wasman.2011.09.010
42	Gao, D. Y., Zhang, L., & Nokken, M. (2017). Mechanical behavior of recycled coarse aggregate concrete reinforced with steel fibers under direct shear. *Cement & Concrete Composites, 79*, 1-8. doi: 10.1016/j.cemconcomp.2017.01.006
43	Garcia-Gonzalez, J., Rodriguez-Robles, D., Juan-Valdes, A., Moran-del Pozo, J. M., & Guerra-Romero, M. I. (2014). Pre-Saturation Technique of the Recycled Aggregates: Solution to the Water Absorption Drawback in the Recycled Concrete Manufacture. *Materials, 7*(9), 6224-6236. doi: 10.3390/ma7096224
44	Gomez-Meijide, B., Perez, I., & Pasandin, A. R. (2016). Recycled construction and demolition waste in Cold Asphalt Mixtures: evolutionary properties. *Journal of Cleaner Production, 112*, 588-598. doi: 10.1016/j.jclepro.2015.08.038
45	Gomez-Meijide, B., Perez, I., Airey, G., & Thom, N. (2015). Stiffness of cold asphalt mixtures with recycled aggregates from construction and demolition waste. *Construction and Building Materials, 77*, 168-178. doi: 10.1016/j.conbuildmat.2014.12.045
46	Gualtieri, A. F. (2013). Recycling asbestos-containing material (ACM) from construction and demolition waste (CDW). In Handbook of recycled concrete and demolition waste (pp. 500-525).
47	Hao, J. L., Hills, M. J., & Tam, V. W. Y. (2008). The effectiveness of Hong Kong's Construction Waste Disposal Charging Scheme. *Waste Management & Research, 26*(6), 553-558. doi: 10.1177/0734242x07085345
48	Hiete, M., Stengel, J., Ludwig, J., & Schultmann, F. (2011). Matching construction and demolition waste supply to recycling demand: a regional management chain model. *Building Research and Information, 39*(4), 333-351. doi: 10.1080/09613218.2011.576849
49	Ho, N. Y., Lee, Y. P. K., Lim, W. F., Zayed, T., Chew, K. C., Low, G. L., & Ting, S. K. (2013). Efficient Utilization of Recycled Concrete Aggregate in Structural Concrete. *Journal of Materials in Civil Engineering, 25*(3), 318-327. doi: 10.1061/(asce)mt.1943-5533.0000587
50	Hou, Y. Q., Ji, X. P., Zou, L., Liu, S., & Su, X. L. (2016). Performance of cement-stabilised crushed brick aggregates in asphalt pavement base and subbase applications. *Road Materials and Pavement Design, 17*(1), 120-135. doi: 10.1080/14680629.2015.1064466
51	Hu, M. M., van der Voet, E., & Huppes, G. (2010). Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing. *Journal of Industrial Ecology, 14*(3), 440-456. doi: 10.1111/j.1530-9290.2010.00245.x
52	Huang, S. L., & Hsu, W. L. (2003). Materials flow analysis and emergy evaluation of Taipei's urban construction. *Landscape and Urban Planning, 63*(2), 61-74. doi: 10.1016/s0169-2046(02)00152-4
53	Huang, S., Zhao, X., Sun, Y. Q., Ma, J. L., Gao, X. F., Xie, T., . . . Zhao, Y. C. (2016). Spatial distribution of organic pollutants in industrial construction and demolition waste and their mutual interaction on an abandoned pesticide manufacturing plant. *Environmental Science-Processes & Impacts, 18*(4), 482-492. doi: 10.1039/c6em00019c
54	Huang, S., Zhao, X., Sun, Y. Q., Ma, J. L., Gao, X. F., Xie, T., . . . Zhao, Y. C. (2017). Pollution of hazardous substances in industrial construction and demolition wastes and their multi-path risk within

	an abandoned pesticide manufacturing plant. *Frontiers of Environmental Science & Engineering, 11*(1), 13. doi: 10.1007/s11783-017-0901-2
55	Iden, S. C., Delay, M., Frimmel, F. H., & Durner, W. (2008). Assessing contaminant mobilization from waste materials: Application of Bayesian parameter estimation to batch extraction tests at varying liquid-to-solid ratios. *Environmental Science & Technology, 42*(10), 3717-3723. doi: 10.1021/es702171z
56	Jain, P., Powell, J., & Tolaymat, T. (2015). Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/111, 2015.
57	Jang, Y. C., & Townsend, T. G. (2001). Occurrence of organic pollutants in recovered soil fines from construction and demolition waste. *Waste Management, 21*(8), 703-715. doi: 10.1016/s0956-053x(01)00007-1
58	Johnson, C. A., Moench, H., & Brandenberger, S. (1999). Assessing the potential long-term behavior of the landfill fraction of sorted demolition wastes. *Journal of Environmental Quality, 28*(4), 1061-1067.
59	Jung, J. S., Song, S. H., Jun, M. H., & Park, S. S. (2015). A comparison of economic feasibility and emission of carbon dioxide for two recycling processes. *Ksce Journal of Civil Engineering, 19*(5), 1248-1255. doi: 10.1007/s12205-015-0708-2
60	Kalbe, U., Berger, W., Eckardt, J., & Simon, F. G. (2008). Evaluation of leaching and extraction procedures for soil and waste. *Waste Management, 28*(6), 1027-1038. doi: 10.1016/j.wasman.2007.03.008
61	Kanellopoulos, A., Nicolaides, D., & Petrou, M. F. (2014). Mechanical and durability properties of concretes containing recycled lime powder and recycled aggregates. *Construction and Building Materials, 53*, 253-259. doi: 10.1016/j.conbuildmat.2013.11.102
62	Kang, H., & Kee, S. H. (2017). Improving the Quality of Mixed Recycled Coarse Aggregates from Construction and Demolition Waste Using Heavy Media Separation with Fe3O4 Suspension. *Advances in Materials Science and Engineering*, 1-12. doi: 10.1155/2017/8753659
63	Karavezyris, V. (2007). Report: Treatment of commercial, construction and demolition waste in North Rhine-Westphalia: policy-making and operation options. *Waste Management & Research, 25*(2), 183-189. doi: 10.1177/0734242x07075249
64	Kern, A. P., Dias, M. F., Kulakowski, M. P., & Gomes, L. P. (2015). Waste generated in high-rise buildings construction: A quantification model based on statistical multiple regression. *Waste Management, 39*, 35-44. doi: 10.1016/j.wasman.2015.01.043
65	Kralj, D. (2009). Experimental study of recycling lightweight concrete with aggregates containing expanded glass. *Process Safety and Environmental Protection, 87*(4), 267-273. doi: 10.1016/j.psep.2009.03.003
66	Kruger, O., Kalbe, U., Berger, W., Simon, F. G., & Meza, S. L. (2012). Leaching experiments on the release of heavy metals and PAH from soil and waste materials. *Journal of Hazardous Materials, 207*, 51-55. doi: 10.1016/j.jhazmat.2011.02.016

67	Kucukvar, M., Egilmez, G., & Tatari, O. (2014). Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life-cycle analysis. *Waste Management & Research, 32*(6), 500-508. doi: 10.1177/0734242x14536457
68	Kucukvar, M., Egilmez, G., & Tatari, O. (2016). Life Cycle Assessment and Optimization-Based Decision Analysis of Construction Waste Recycling for a LEED-Certified University Building. *Sustainability, 8*(1), 13. doi: 10.3390/su8010089
69	Kumar, R. (2017). Influence of recycled coarse aggregate derived from construction and demolition waste (CDW) on abrasion resistance of pavement concrete. *Construction and Building Materials, 142*, 248-255. doi: 10.1016/j.conbuildmat.2017.03.077
70	Lau, H. H., Whyte, A., & Law, P. L. (2008). Composition and characteristics of construction waste generated by residential housing project. *International Journal of Environmental Research, 2*(3), 261-268.
71	Lee, J. Y., Moon, S. H., Yi, M. J., & Yun, S. T. (2008). Groundwater contamination with petroleum hydrocarbons, chlorinated solvents and high pH: implications for multiple sources. *Quarterly Journal of Engineering Geology and Hydrogeology, 41*, 35-47. doi: 10.1144/1470-9236/07-021
72	Leite, F. D., Motta, R. D., Vasconcelos, K. L., & Bernucci, L. (2011). Laboratory evaluation of recycled construction and demolition waste for pavements. *Construction and Building Materials, 25*(6), 2972-2979. doi: 10.1016/j.conbuildmat.2010.11.105
73	Li, J. R., Ding, Z. K., Mi, X. M., & Wang, J. Y. (2013). A model for estimating construction waste generation index for building project in China. *Resources Conservation and Recycling, 74*, 20-26. doi: 10.1016/j.resconrec.2013.02.015
74	Li, J. X., & Yang, E. H. (2017). Macroscopic and microstructural properties of engineered cementitious composites incorporating recycled concrete fines. *Cement & Concrete Composites, 78*, 33-42. doi: 10.1016/j.cemconcomp.2016.12.013
75	Lovato, P. S., Possan, E., Dal Molin, D. C. C., Masuero, A. B., & Ribeiro, J. L. D. (2012). Modeling of mechanical properties and durability of recycled aggregate concretes. *Construction and Building Materials, 26*(1), 437-447. doi: 10.1016/j.conbuildmat.2011.06.043
76	Lu, W. S., & Yuan, H. P. (2010). Exploring critical success factors for waste management in construction projects of China. *Resources Conservation and Recycling, 55*(2), 201-208. doi: 10.1016/j.resconrec.2010.09.010
77	Lu, W. S., Chen, X., Ho, D. C. W., & Wang, H. D. (2016). Analysis of the construction waste management performance in Hong Kong: the public and private sectors compared using big data. *Journal of Cleaner Production, 112*, 521-531. doi: 10.1016/j.jclepro.2015.06.106
78	Lu, W. S., Chen, X., Peng, Y., & Shen, L. Y. (2015). Benchmarking construction waste management performance using big data. *Resources Conservation and Recycling, 105*, 49-58. doi: 10.1016/j.resconrec.2015.10.013
79	Lu, W. S., Yuan, H. P., Li, J. R., Hao, J. J. L., Mi, X. M., & Ding, Z. K. (2011). An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Waste Management, 31*(4), 680-687. doi: 10.1016/j.wasman.2010.12.004

80	Lu, W., & Yuan, H. (2011). A framework for understanding waste management studies in construction. *Waste Management, 31*(6), 1252-1260. doi: https://doi.org/10.1016/j.wasman.2011.01.018
81	Lu, W., Chen, X., Ho, D. C., & Wang, H. (2016). Analysis of the construction waste management performance in Hong Kong: the public and private sectors compared using big data. Journal of Cleaner Production, 112, 521-531.
82	Lu, W., Webster, C., Peng, Y., Chen, X., & Zhang, X. (2017). Estimating and calibrating the amount of building-related construction and demolition waste in urban China. International Journal of Construction Management, 17(1), 13-24.
83	Lye, C.-Q., Dhir, R. K., Ghataora, G. S., & Li, H. (2016). Creep strain of recycled aggregate concrete. *Construction and Building Materials, 102*, 244-259. doi: https://doi.org/10.1016/j.conbuildmat.2015.10.181
84	Malia, M., de Brito, J., Pinheiro, M. D., & Bravo, M. (2013). Construction and demolition waste indicators. *Waste Management & Research, 31*(3), 241-255. doi: 10.1177/0734242x12471707
85	Marzouk, M., & Azab, S. (2014). Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. *Resources Conservation and Recycling, 82*, 41-49. doi: 10.1016/j.resconrec.2013.10.015
86	Matias, D., de Brito, J., Rosa, A., & Pedro, D. (2013). Mechanical properties of concrete produced with recycled coarse aggregates - Influence of the use of superplasticizers. *Construction and Building Materials, 44*, 101-109. doi: 10.1016/j.conbuildmat.2013.03.011
87	Mercader-Moyano, P., & Ramirez-de-Arellano-Agudo, A. (2013). Selective classification and quantification model of C&D waste from material resources consumed in residential building construction. *Waste Management & Research, 31*(5), 458-474. doi: 10.1177/0734242x13477719
88	Mercante, I. T., Bovea, M. D., Ibanez-Fores, V., & Arena, A. P. (2012). Life cycle assessment of construction and demolition waste management systems: a Spanish case study. *International Journal of Life Cycle Assessment, 17*(2), 232-241. doi: 10.1007/s11367-011-0350-2
89	Miranda, L. F. R., Constantino, C. S., Monich, C. R., & Neto, A. A. D. (2013). Use of Recycled Sand Produced at Construction Sites in Bedding Mortars. *Journal of Materials in Civil Engineering, 25*(2), 236-242. doi: 10.1061/(asce)mt.1943-5533.0000593
90	Miranda, L. F. R., Lapenda, M. P., Teixeira, S. H. C., & Vogt, V. (2014). Rational Procedure for Composition of Screed Mortar with Recycled Sand at a Construction Site. *Journal of Materials in Civil Engineering, 26*(5), 855-862. doi: 10.1061/(asce)mt.1943-5533.0000877
91	Nassar, A. I., Mohammed, M. K., Thom, N., & Parry, T. (2016). Mechanical, durability and microstructure properties of Cold Asphalt Emulsion Mixtures with different types of filler. *Construction and Building Materials, 114*, 352-363. doi: 10.1016/j.conbuildmat.2016.03.112
92	Osmani, M., Glass, J., & Price, A. D. (2008). Architects' perspectives on construction waste reduction by design. Waste management, 28(7), 1147-1158.
93	Oygard, J. K., Gjengedal, E., & Mage, A. (2005). Mass-balance estimation of heavy metals and selected anions at a landfill receiving MSWI bottom ash and mixed construction wastes. *Journal of Hazardous Materials, 123*(1-3), 70-75. doi: 10.1016/j.jhazmat.2005.04.022

94	Park, J., & Tucker, R. (2017). Overcoming barriers to the reuse of construction waste material in Australia: a review of the literature. International Journal of Construction Management, 17(3), 228-237.
95	Pasandin, A. R., & Perez, I. (2013). Laboratory evaluation of hot-mix asphalt containing construction and demolition waste. *Construction and Building Materials, 43*, 497-505. doi: 10.1016/j.conbuildmat.2013.02.052
96	Pasandin, A. R., & Perez, I. (2014). Mechanical properties of hot-mix asphalt made with recycled concrete aggregates coated with bitumen emulsion. *Construction and Building Materials, 55*, 350-358. doi: 10.1016/j.conbuildmat.2014.01.053
97	Penacho, P., de Brito, J., & Veiga, M. R. (2014). Physico-mechanical and performance characterization of mortars incorporating fine glass waste aggregate. *Cement & Concrete Composites, 50*, 47-59. doi: 10.1016/j.cemconcomp.2014.02.007
98	Poon, C. S., Ann, T. W., & Ng, L. H. (2001). On-site sorting of construction and demolition waste in Hong Kong. Resources, conservation and recycling, 32(2), 157-172
99	Poon, C. S., Yu, A. T. W., Wong, A., & Yip, R. (2013). Quantifying the Impact of Construction Waste Charging Scheme on Construction Waste Management in Hong Kong. *Journal of Construction Engineering and Management-Asce, 139*(5), 466-479. doi: 10.1061/(asce)co.1943-7862.0000631
100	Poon, C. S., Yu, A. T., & Jaillon, L. (2004). Reducing building waste at construction sites in Hong Kong. Construction Management and Economics, 22(5), 461-470
101	Porwal, A., & Hewage, K. N. (2012). Building Information Modeling-Based Analysis to Minimize Waste Rate of Structural Reinforcement. *Journal of Construction Engineering and Management-Asce, 138*(8), 943-954. doi: 10.1061/(asce)co.1943-7862.0000508
102	Rivero, A. J., Sathre, R., & Navarro, J. G. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources Conservation and Recycling, 108*, 171-181. doi: 10.1016/j.resconrec.2016.01.014
103	Roussat, N., Mehu, J., Abdelghafour, M., & Brula, P. (2008). Leaching behaviour of hazardous demolition waste. *Waste Management, 28*(11), 2032-2040. doi: 10.1016/j.wasman.2007.10.019
104	Shin, E., & Kang, J. (2015). Migration of calcium hydroxide compounds in construction waste soil. *Advances in Environmental Research-an International Journal, 4*(3), 183-196. doi: 10.12989/aer.2015.4.3.183
105	Shin, W. S., Na, K. R., & Kim, Y. K. (2016). Adsorption of metal ions from aqueous solution by recycled aggregate: estimation of pretreatment effect. *Desalination and Water Treatment, 57*(20), 9366-9374. doi: 10.1080/19443994.2015.1029528
106	Silva, R. V., de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials, 65*, 201-217. doi: https://doi.org/10.1016/j.conbuildmat.2014.04.117
107	Silva, R. V., de Brito, J., & Dhir, R. K. (2015a). Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete. *Engineering Structures, 100*, 31-42. doi: https://doi.org/10.1016/j.engstruct.2015.06.004
108	Silva, R. V., de Brito, J., & Dhir, R. K. (2015b). Tensile strength behaviour of recycled aggregate concrete. *Construction and Building Materials, 83*, 108-118. doi: 10.1016/j.conbuildmat.2015.03.034

109	Sim, J., & Park, C. (2011). Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. *Waste Management, 31*(11), 2352-2360. doi: 10.1016/j.wasman.2011.06.014
110	Simion, I. M., Ghinea, C., Maxineasa, S. G., Taranu, N., Bonoli, A., & Gavrilescu, M. (2013). Ecological footprint applied in the assessment of construction and demolition waste integrated management. *Environmental Engineering and Management Journal, 12*(4), 779-788.
111	Solis-Guzman, J., Marrero, M., Montes, M. V., & Ramirez-De-Arellano, A. (2009). A Spanish model for quantification and management of construction waste. *Waste Management, 29*(9), 2542-2548. doi: 10.1016/j.wasman.2009.05.009
112	Sou, W. I., Chu, A., & Chiueh, P. T. (2016). Sustainability assessment and prioritisation of bottom ash management in Macao. *Waste Management & Research, 34*(12), 1275-1282. doi: 10.1177/0734242x16665914
113	Soutsos, M., & Fulton, M. C. (2016). Recycling of demolition waste in Merseyside. *Proceedings of the Institution of Civil Engineers-Construction Materials, 169*(2), 54-66. doi: 10.1680/coma.15.00012
114	Spoerri, A., Lang, D. J., Binder, C. R., & Scholz, R. W. (2009). Expert-based scenarios for strategic waste and resource management planning-C&D waste recycling in the Canton of Zurich, Switzerland. *Resources Conservation and Recycling, 53*(10), 592-600. doi: 10.1016/j.resconrec.2009.04.011
115	Stefanidou, M., Anastasiou, E., & Filikas, K. G. (2014). Recycled sand in lime-based mortars. *Waste Management, 34*(12), 2595-2602. doi: 10.1016/j.wasman.2014.09.005
116	Suh, J. Y. (2004). Hydrogeochemical studies of groundwater from reclaimed land adjacent to Rozelle Bay, Sydney, Australia. *Geosciences Journal, 8*(3), 301-312. doi: 10.1007/bf02910249
117	Tam, V. W. Y. (2008). On the effectiveness in implementing a waste-management-plan method in construction. *Waste Management, 28*(6), 1072-1080. doi: 10.1016/j.wasman.2007.04.007
118	Tam, V. W. Y., & Hao, J. J. L. (2016). Attitudes towards recycling on construction sites. *Proceedings of the Institution of Civil Engineers-Waste and Resource Management, 169*(3), 6. doi: 10.1680/jwarm.15.00006
119	Tam, V. W. Y., & Tam, C. M. (2009). Parameters for assessing recycled aggregate and their correlation. *Waste Management & Research, 27*(1), 52-58. doi: 10.1177/0734242x07079875
120	Tam, V. W. Y., Fung, I. W. H., Sing, M. C. P., & Ogunlana, S. O. (2015a). Best practice of prefabrication implementation in the Hong Kong public and private sectors. *Journal of Cleaner Production, 109*, 216-231. doi: 10.1016/j.jclepro.2014.09.045
121	Tam, V. W. Y., Kotrayothar, D., & Xiao, J. Z. (2015b). Long-term deformation behaviour of recycled aggregate concrete. *Construction and Building Materials, 100*, 262-272. doi: 10.1016/j.conbuildmat.2015.10.013
122	Tam, V. W. Y., Tam, C. M., & Le, K. N. (2007). Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. *Resources Conservation and Recycling, 50*(1), 82-101. doi: 10.1016/j.resconrec.2006.05.012
123	Tam, V. W., & Tam, C. M. (2008). Waste reduction through incentives: a case study. *Building Research and Information, 36*(1), 37-43. doi: 10.1080/09613210701417003
124	Tam, V. W., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). Construction and Building Materials, 172, 272-292.

125	Udawatta, N., Zuo, J., Chiveralls, K., & Zillante, G. (2015a). Attitudinal and behavioural approaches to improving waste management on construction projects in Australia: benefits and limitations. *International Journal of Construction Management, 15*(2), 137-147. doi: 10.1080/15623599.2015.1033815
126	Udawatta, N., Zuo, J., Chiveralls, K., & Zillante, G. (2015b). Improving waste management in construction projects: An Australian study. *Resources Conservation and Recycling, 101*, 73-83. doi: 10.1016/j.resconrec.2015.05.003
127	Ulsen, C., Kahn, H., Hawlitschek, G., Masini, E. A., Angulo, S. C., & John, V. M. (2013). Production of recycled sand from construction and demolition waste. *Construction and Building Materials, 40*, 1168-1173. doi: 10.1016/j.conbuildmat.2012.02.004
128	Van Praagh, M., & Modin, H. (2016). Leaching of chloride, sulphate, heavy metals, dissolved organic carbon and phenolic organic pesticides from contaminated concrete. *Waste Management, 56*, 352-358. doi: 10.1016/j.wasman.2016.07.009
129	Vegas, I., Broos, K., Nielsen, P., Lambertz, O., & Lisbona, A. (2015). Upgrading the quality of mixed recycled aggregates from construction and demolition waste by using near-infrared sorting technology. *Construction and Building Materials, 75*, 121-128. doi: 10.1016/j.conbuildmat.2014.09.109
130	Vieira, T., Alves, A., de Brito, J., Correia, J. R., & Silva, R. V. (2016). Durability-related performance of concrete containing fine recycled aggregates from crushed bricks and sanitary ware. *Materials & Design, 90*, 767-776. doi: 10.1016/j.matdes.2015.11.023
131	Vitale, P., Arena, N., Di Gregorio, F., & Arena, U. (2017). Life cycle assessment of the end-of-life phase of a residential building. *Waste Management, 60*, 311-321. doi: 10.1016/j.wasman.2016.10.002
132	Wang, J. Y., Li, Z. D., & Tam, V. W. Y. (2014). Critical factors in effective construction waste minimization at the design stage: A Shenzhen case study, China. *Resources Conservation and Recycling, 82*, 1-7. doi: 10.1016/j.resconrec.2013.11.003
133	Wang, J. Y., Yuan, H. P., Kang, X. P., & Lu, W. S. (2010). Critical success factors for on-site sorting of construction waste: A china study. *Resources Conservation and Recycling, 54*(11), 931-936. doi: 10.1016/j.resconrec.2010.01.012
134	Wang, J., Li, Z., & Tam, V. W. (2015). Identifying best design strategies for construction waste minimization. Journal of Cleaner Production, 92, 237-247.
135	Wang, J., Wu, H., Duan, H., Zillante, G., Zuo, J., & Yuan, H. (2018). Combining Life Cycle Assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study. *Journal of Cleaner Production, 172*, 3154-3166.
136	Warren, J. D., Chong, W. K., & Kim, C. (2007). Recycling construction and demolition waste for construction in Kansas City metropolitan area, Kansas and Missouri. *Transportation Research Record*, 193-200. doi: 10.3141/2011-21
137	Wehrer, M., & Totsche, K. U. (2008). Effective rates of heavy metal release from alkaline wastes - Quantified by column outflow experiments and inverse simulations. *Journal of Contaminant Hydrology, 101*(1-4), 53-66. doi: 10.1016/j.jconhyd.2008.07.005

138	Wiedenhofer, D., Steinberger, J. K., Eisenmenger, N., & Haas, W. (2015). Maintenance and Expansion Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25. *Journal of Industrial Ecology, 19*(4), 538-551. doi: 10.1111/jiec.12216
139	Won, J., & Cheng, J. C. P. (2017). Identifying potential opportunities of building information modeling for construction and demolition waste management and minimization. *Automation in Construction, 79*, 3-18. doi: 10.1016/j.autcon.2017.02.002
140	Won, J., Cheng, J. C. P., & Lee, G. (2016). Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea. *Waste Management, 49*, 170-180. doi: 10.1016/j.wasman.2015.12.026
141	Wu, H. Y., Duan, H. B., Wang, J. Y., Wang, T., & Wang, X. F. (2015). Quantification of carbon emission of construction waste by using streamlined LCA: a case study of Shenzhen, China. *Journal of Material Cycles and Waste Management, 17*(4), 637-645. doi: 10.1007/s10163-015-0404-9
142	Wu, H. Y., Duan, H. B., Zheng, L. N., Wang, J. Y., Niu, Y. N., & Zhang, G. M. (2016a). Demolition waste generation and recycling potentials in a rapidly developing flagship megacity of South China: Prospective scenarios and implications. *Construction and Building Materials, 113*, 1007-1016. doi: 10.1016/j.conbuildmat.2016.03.130
143	Wu, H. Y., Wang, J. Y., Duan, H. B., Ouyang, L., Huang, W. K., & Zuo, J. (2016b). An innovative approach to managing demolition waste via GIS (geographic information system): a case study in Shenzhen city, China. *Journal of Cleaner Production, 112*, 494-503. doi: 10.1016/j.jclepro.2015.08.096
144	Wu, Z. Z., Yu, A. T. W., & Shen, L. Y. (2017). Investigating the determinants of contractor's construction and demolition waste management behaviour in Mainland China. *Waste Management, 60*, 290-300. doi: 10.1016/j.wasman.2016.09.001
145	Wu, Z., Yu, A. T. W., Shen, L., & Liu, G. (2014). Quantifying construction and demolition waste: An analytical review. *Waste Management, 34*(9), 1683-1692. doi: https://doi.org/10.1016/j.wasman.2014.05.010
146	Xuan, D. X., Molenaar, A. A. A., & Houben, L. J. M. (2016). Shrinkage cracking of cement treated demolition waste as a road base. *Materials and Structures, 49*(1-2), 631-640. doi: 10.1617/s11527-015-0524-7
147	Xue, C. Z., Shen, A. Q., Guo, Y. C., & He, T. Q. (2016). Utilization of Construction Waste Composite Powder Materials as Cementitious Materials in Small-Scale Prefabricated Concrete. *Advances in Materials Science and Engineering*, 1-11. doi: 10.1155/2016/8947935
148	Yeheyis, M., Hewage, K., Alam, M. S., Eskicioglu, C., & Sadiq, R. (2013). An overview of construction and demolition waste management in Canada: a life cycle analysis approach to sustainability. *Clean Technologies and Environmental Policy, 15*(1), 81-91. doi: 10.1007/s10098-012-0481-6
149	Younis, K. H., & Pilakoutas, K. (2013). Strength prediction model and methods for improving recycled aggregate concrete. *Construction and Building Materials, 49*, 688-701. doi: 10.1016/j.conbuildmat.2013.09.003

150	Yu, A. T. W., Poon, C. S., Wong, A., Yip, R., & Jaillon, L. (2013). Impact of Construction Waste Disposal Charging Scheme on work practices at construction sites in Hong Kong. *Waste Management, 33*(1), 138-146. doi: 10.1016/j.wasman.2012.09.023
151	Yuan, H. P., & Wang, J. Y. (2014). A system dynamics model for determining the waste disposal charging fee in construction. *European Journal of Operational Research, 237*(3), 988-996. doi: 10.1016/j.ejor.2014.02.034
152	Yuan, H., & Shen, L. (2011). Trend of the research on construction and demolition waste management. *Waste Management, 31*(4), 670-679. doi: https://doi.org/10.1016/j.wasman.2010.10.030
153	Yuan, H., Wu, H., & Zuo, J. (2018). Understanding Factors Influencing Project Managers' Behavioral Intentions to Reduce Waste in Construction Projects. *Journal of Management in Engineering*, *34*(6), 04018031.
154	Zega, C. J., Villagran-Zaccardi, Y. A., & Di Maio, A. A. (2010). Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. *Materials and Structures, 43*(1-2), 195-202. doi: 10.1617/s11527-009-9480-4
155	Zhao, W., Leeftink, R. B., & Rotter, V. S. (2010). Evaluation of the economic feasibility for the recycling of construction and demolition waste in China-The case of Chongqing. *Resources Conservation and Recycling, 54*(6), 377-389. doi: 10.1016/j.resconrec.2009.09.003
156	Zheng, L. N., Wu, H. Y., Zhang, H., Duan, H. B., Wang, J. Y., Jiang, W. P., Song, Q. B. (2017). Characterizing the generation and flows of construction and demolition waste in China. *Construction and Building Materials, 136*, 405-413. doi: 10.1016/j.conbuildmat.2017.01.055

Table A-2.2 Key words clusters

Cluster	Classification	Keywords
Cluster 1	Pollutant compositions	heavy metals (e.g. copper and chromium), organic matter (e.g. polycyclic aromatic hydrocrack, carbon, methane, sulfuret and hydrogen sulphide)
	Effect mechanism	sorption, adsorption, release, immobilization, incineration, pyrolysis
	Impact approach	leachate, biomass, landfill gas, pesticides (come from the demolition waste of abandoned pesticide manufacturing plant)
	Affected surroundings	water, groundwater, soils
	Testing methods	leaching tests
Cluster 2	Recyclable waste materials	Concrete, cement mortar, sand, glass waste
	Recycled products	Recycled aggregate, recycled fine aggregate, recycled sand, recycled glass, hot mix asphalt
	Use of recycled products	Subbase, pavement, reclaimed asphalt pavement, filler

Cluster 3	Performance category	Behaviour, performance, mechanical properties, physical properties, engineering properties, mechanical behaviour, permanent deformation, curing condition
	Performance indicators	Strength, compressive strength, bond strength, durability, stiffness, porosity, conductivity, microstructure, density, elasticity, modulus of elasticity, hardened properties
Cluster 4	Waste generation	Generation, waste generation rate, quantification, estimation
	Waste reduction	Reduction, minimizations
		Design, on site
		Attitudes, planned behaviour
		Charging scheme
	Economic performance	Circular economy, economic feasibility, economic viability
	Information tech	Information, GIS, BIM, Big Data
Cluster 5	Industrial ecology	Environmental impact, mass flows, challeges

Table A-3.1 Review list of approaches to assess the management performance and impacts of C&D waste

No.	Author	Region	Paper tittle	Journal
1	Chung and Lo, (2003)	Hong Kong	Evaluating sustainability in waste management: the case of construction and demolition, chemical and clinical wastes in Hong Kong	Resources Conservation and Recycling
2	Klang et al., (2003)	Norway and Sweden	Sustainable management of demolition waste - an integrated model for the evaluation of environmental, economic and social aspects	Resources Conservation and Recycling
3	Begum et al., (2006)	Malaysia	A benefit-cost analysis on the economic feasibility of construction waste minimization: The case of Malaysia	Resources Conservation and Recycling
4	Duran et al., (2006)	Ireland	A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland	Resources Conservation and Recycling
5	Bohne et al., (2008)	Norway	Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level	Journal of Industrial Ecology

6	Gomes et al., (2008)	Brazil	Multicriteria decision making applied to waste recycling in Brazil	Omega-International Journal of Management Science
7	da Rocha and Sattler, (2009)	Brazil	A discussion on the reuse of building components in Brazil: An analysis of major social, economic and legal factors	Resources Conservation and Recycling
8	Lu et al., (2009)	Hong Kong	Simulation Approach to Evaluating Cost Efficiency of Selective Demolition Practices: Case of Hong Kong's Kai Tak Airport Demolition	Journal of Construction Engineering and Management
9	Roussat et al., (2009)	N/A	Indicators to assess the recovery of natural resources contained in demolition waste	Waste Management & Research
10	Shen et al., (2009)	Hong Kong	Benefit analysis on replacing in situ concreting with precast slabs for temporary construction works in pursuing sustainable construction practice	Resources Conservation and Recycling
11	Merino et al., (2010)	Spain	Sustainable construction: construction and demolition waste reconsidered	Waste Management & Research
12	Ortiz et al., (2010)	Spain	Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain	Waste Management
13	Tam et al., (2010)	Australia, Hong Kong, Japan	Cross-cultural comparison of concrete recycling decision-making and implementation in construction industry	Waste Management
14	Zhao et al., (2010)	China/Chongqing	Evaluation of the economic feasibility for the recycling of construction and demolition waste in China-The case of Chongqing	Resources Conservation and Recycling
15	Yuan et al., (2011)	China/Shanghai	Emergy analysis of the recycling options for construction and demolition waste	Waste Management
16	Zhao et al., (2011)	China/Chongqing	A system dynamics model for evaluating the alternative of type in construction and demolition waste recycling centre - The case of Chongqing, China	Resources Conservation and Recycling

17	Manowong, (2012)	Thailand	Investigating factors influencing construction waste management efforts in developing countries: an experience from Thailand	Waste Management & Research
18	Mercante et al., (2012)	Spain	Life cycle assessment of construction and demolition waste management systems: a Spanish case study	International Journal of Life Cycle Assessment
19	Ye et al., (2012)	China/Shenzhen	Simulating effects of management measures on the improvement of the environmental performance of construction waste management	Resources Conservation and Recycling
20	Yuan, (2012)	China/Shenzhen	A model for evaluating the social performance of construction waste management	Waste Management
21	Simion et al., (2013)	Italy	Ecological footprint applied in the assessment of construction and demolition waste integrated management	Environmental Engineering and Management Journal
22	Srour et al., (2013)	Lebanon	Pilot-based assessment of the economics of recycling construction demolition waste	Waste Management & Research
23	Yuan (2013)	N/A	Key indicators for assessing the effectiveness of waste management in construction projects	Ecological Indicators
24	Marzouk and Azab, (2014)	Egypt	Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics	Resources Conservation and Recycling
25	Tam et al., (2014)	China/Shenzhen	System dynamic modelling on construction waste management in Shenzhen, China	Waste Management & Research
26	Butera et al., (2015)	Denmark	Life cycle assessment of construction and demolition waste management	Waste Management
27	Dahlbo et al., (2015)	Finland	Construction and demolition waste management - a holistic evaluation of environmental performance	Journal of Cleaner Production
28	Dejkovski, (2016)	Australia	Assessing the environmental performance of construction materials testing using EMS: An Australian study	Waste Management

39	Ding et al., (2016a)	China/Shenzhen	An agent based environmental impact assessment of building demolition waste management: Conventional versus green management	Journal of Cleaner Production
30	Ding et al., (2016b)	China/Shenzhen	A system dynamics-based environmental performance simulation of construction waste reduction management in China	Waste Management
31	Kucukvar et al., (2016)	USA	Life Cycle Assessment and Optimization-Based Decision Analysis of Construction Waste Recycling for a LEED-Certified University Building	Sustainability
32	Penteado and Rosado, (2016)	Brazil	Comparison of scenarios for the integrated management of construction and demolition waste by life cycle assessment: A case study in Brazil	Waste Management & Research
33	Zambrana-Vasquez et al., (2016)	Spain	Analysis of the environmental performance of life-cycle building waste management strategies in tertiary buildings	Journal of Cleaner Production
34	Chau et al., (2017)	Hong Kong	Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building	Applied Energy
35	Marrero et al., (2017)	Spain	Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land	Resources Conservation and Recycling
36	Wang et al., (2018)	China/Shenzhen	Combining Life Cycle Assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study	Journal of Cleaner Production

Table A-5.1 Generation and fates of C&D waste in Australia, 2006-07 to 2016-17 (unit: million ton)

	2007	**2009**	**2010**	**2011**	**2014**	**2015**	**2016**	**2017**
Generation[1]	16.9	18.5	18.4	18.4	17.9	19.4	20.1	20.4
Recycling[2]	10.1	11.1	11.3	12.1	11.5	12.4	13.5	13.6
Landfilling[3]	6.6	7.3	7	6.2	6.2	6.7	6.4	6.7
Energy recovery[4]	0.2	0.1	0.1	0.1	0.2	0.3	0.2	0.1

Note: *Data extracted from Australia National Waste Report 2018 database (DEE, 2018)*

[1.] National waste report 2018 pp91, data table for figure 2, line 1;

[2.] National waste report 2018 pp91, data table a for figure 3, line 1

[3.] National waste report 2018 pp91, data table b for figure 3, line 1

[4.] Energy recovery=generation-recycling-landfilling

Table A-5.2 Australian C&D waste generation, population and economic activity by state and territory in 2017

	ACT	**NSW**	**NT**	**QLD**	**SA**	**TAS**	**VIC**	**WA**	**Total**
C&D waste generation % by weight	1.0%	33.1%	0.7%	20.2%	6.6%	0.1%	29.7%	8.6%	100.0%
Population %	1.5%	28.9%	0.9%	18.1%	6.4%	1.9%	23.2%	9.5%	100.0%
GSP %	2.2%	33.0%	1.5%	18.3%	6.0%	1.7%	23.6%	13.8%	100.0%

Note: Data extracted from *Australia National Waste Report 2018 database* (DEE, 2018)

Table A-6.1 Environmental impacts for 1 t of C&D waste in scenario 0.0

	Scenario 0.0 (1 t C&D waste)	Unit	Waste collection and onsite sorting	Transportation	Waste pre-processing (Sorting)	Recycling	Energy recovery	Landfilling	Total
EI1	GWP 100 years	kg CO2-Equiv.	1.18E-01	1.78E-01	2.69E+00	-1.37E+05	-9.99E+02	3.86E+04	-9.93E+04
EI2	AP	kg SO2-Equiv.	1.10E-03	1.68E-03	1.81E-02	-3.79E+02	-2.70E+00	3.95E+01	-3.42E+02
EI3	EP	kg Phosphate-Equiv.	9.64E-05	1.82E-04	4.43E-03	-1.99E+01	-5.39E-01	5.27E+00	-1.52E+01
EI4	ODP, steady state	kg R11-Equiv.	5.78E-16	2.75E-15	6.08E-13	3.50E-03	-6.81E-09	-1.65E-04	3.34E-03
EI5	ADP elements	kg Sb-Equiv.	3.40E-08	3.49E-08	3.59E-06	-1.71E-01	-1.92E-05	3.07E-03	-1.68E-01
EI6	ADP fossil	MJ	2.87E+01	3.17E+01	5.06E+01	-1.55E+06	-4.69E+02	9.35E+04	-1.45E+06
EI7	FAETP inf.	kg DCB-Equiv.	4.08E-03	5.40E-03	2.03E-02	-8.50E+00	-1.42E-01	1.51E+01	6.53E+00
EI8	HTP inf.	kg DCB-Equiv.	2.50E-02	3.24E-02	2.35E-01	-2.93E+04	-9.12E+00	1.08E+03	-2.82E+04
EI9	MAETP inf.	kg DCB-Equiv.	1.64E+01	2.15E+01	1.09E+02	-7.05E+07	-3.74E+02	1.06E+06	-6.95E+07
EI10	POCP	kg Etheme-Equiv.	1.61E-04	1.85E-04	1.98E-03	-6.52E+01	-2.78E-01	1.26E+01	-5.29E+01
EI11	TETP inf.	kg DCB-Equiv.	1.66E-04	2.58E-04	4.99E-03	-2.42E+01	-1.01E-01	3.67E+01	1.24E+01
E12	Land occupation	m^3	0.00E+00	0.00E+00	0.00E+00	1.41E-02	2.48E-04	1.63E-01	1.77E-01

Table A-6.2 Environmental impacts for all generated C&D waste in scenario 0.0

	Scenario 0.0 (1 t C&D waste)	**Unit**	**Waste collection and onsite sorting**	**Transportation**	**Waste pre-processing (Sorting)**	**Recycling**	**Energy recovery**	**Landfilling**	**Total**
EI1	GWP 100 years	kg CO2-Equiv.	2.38E+06	3.58E+06	5.41E+07	-1.44E+12	-2.01E+10	7.89E+11	-6.73E+11
EI2	AP	kg SO2-Equiv.	2.20E+04	3.37E+04	3.64E+05	-3.70E+09	-5.42E+07	8.33E+08	-2.92E+09
EI3	EP	kg Phosphate-Equiv.	1.94E+03	3.66E+03	8.90E+04	-1.48E+08	-1.08E+07	1.07E+08	-5.18E+07
EI4	ODP, steady state	kg R11-Equiv.	1.16E-08	5.53E-08	1.22E-05	4.44E+04	-1.37E-01	-3.79E+03	4.06E+04
EI5	ADP elements	kg Sb-Equiv.	6.83E-01	7.02E-01	7.21E+01	-9.71E+05	-3.85E+02	9.59E+04	-8.75E+05
EI6	ADP fossil	MJ	5.76E+08	6.36E+08	1.02E+09	-1.54E+13	-9.42E+09	2.06E+12	-1.34E+13
EI7	FAETP inf.	kg DCB-Equiv.	8.21E+04	1.09E+05	4.08E+05	1.54E+09	-2.85E+06	2.88E+08	1.82E+09
EI8	HTP inf.	kg DCB-Equiv.	5.02E+05	6.51E+05	4.72E+06	-1.33E+11	-1.83E+08	2.42E+10	-1.09E+11
EI9	MAETP inf.	kg DCB-Equiv.	3.29E+08	4.33E+08	2.19E+09	-3.29E+14	-7.51E+09	2.82E+13	-3.01E+14
EI10	POCP	kg Etheme-Equiv.	3.23E+03	3.71E+03	3.98E+04	-7.64E+08	-5.60E+06	2.60E+08	-5.10E+08
EI11	TETP inf.	kg DCB-Equiv.	3.34E+03	5.19E+03	1.00E+05	4.27E+08	-2.03E+06	7.28E+08	1.15E+09
E12	Land occupation	m^3	0.00E+00	0.00E+00	0.00E+00	2.72E+05	4.99E+03	3.27E+06	3.55E+06

Table A-6.3 Economic impacts for 2017 generation of C&D waste in scenario 0.0

Waste	Stages/Activities	Monetary (AUD)
C&D waste	Waste collection & transportation & Pre-processing	3.62E+09
Masonry materials	Recycling (Masonry materials)	1.37E+09
	Landfilling (Masonry materials)	5.16E+08
Steel	Recycling (Steel)	5.78E+08
	Landfilling (Steel)	8.26E+06
Aluminium	Recycling (Aluminium)	1.26E+08
	Landfilling (Aluminium)	5.16E+05
Copper	Recycling (Copper)	1.99E+08
	Landfilling (Copper)	1.55E+06
Organics (Timber)	Recycling (Timber)	7.98E+07
	Landfilling (Timber)	5.43E+07
Paper & cardboard	Recycling (Paper & cardboard)	1.88E+06
	Landfilling (Paper & cardboard)	7.77E+06
Plastic	Recycling (Plastic)	3.23E+06
	Landfilling (Plastic)	1.14E+07
Glass	Recycling (Glass)	1.78E+06
	Landfilling (Glass)	1.64E+05
TLR	Recycling (TLR)	0.00E+00
	Landfilling (TLR)	2.07E+06
Others	Recycling (Others)	3.48E+08
	Landfilling (Others)	1.78E+06
Total		6.95E+09

Table A-6.4 Social impacts of Cross-regional mobility of C&D waste base scenario

State /territory	Gain + (p full-time equivalent terms)	Lost – (p full-time equivalent terms)	Employment impacts +/- (p full-time equivalent terms)
ACT	328.17	-	328.17
NSW	14.56	972.67	-958.11
VIC	61.88	49.69	12.19
QLD	582.17	276.46	305.71
SA	2.05	31.14	-29.09
WA	-	4.88	-4.88
NT	-	-	-

Table A-7.1 Landfill levy in Australia (2018-19)

State	Waste type	Levy	Note
ACT	MSW	$96.05/t	No landfill fee for C&D waste applied
	C&I	$155.05/t	
	Mixed C&I with >50% recyclable material	$211.55/t	
NSW	Metro area:		Applied to C&D waste regarding the materials
	· Waste	$141.20/t	
	· Virgin excavated natural material	$127.08/t	
	· Shredder floc	$70.60/t	
	Regional area:		
	· Waste	$81.30/t	
	· Virgin excavated natural material	$73.17/t	
	· Shredder floc	$40.65/t	
	Coal washery rejects	$14.80/t	
NT	No landfill levy	N/A	N/A
QLD	Clean earth (Soil)	N/A	The waste levy for all classifications (including C&D waste) is proposed to increase by $5 on 1 July each year. Last updated:21 June 2019
	C&D waste	$75/t	
SA	Metro Adelaide:		Applied to C&D waste regarding the materials
	· Solid waste	$100/t	
	· Shredder floc	$62/t	
	Non-metro Adelaide:		
	· Solid waste	$50/t	
	· Shredder floc	$31/t	
	No levy for packaged asbestos waste		
VIC	Metro and regional:		
	· MSW	$64.30/t	
	· C&I and C&D	$64.30/t	Applied to C&D waste regarding the materials
	Rural:		
	· MSW	$32.22/t	
	· C&I and C&D	$56.36/t	Applied to C&D waste regarding the materials
WA	Putrescible	$70/t	
	Inert $105/m3	$70/t approx.	Applied to C&D waste regarding the materials

Note: C&D waste refers to construction and demolition waste; C&I waste refers to Commercial and industrial waste; MSW refers to Municipal Solid Waste.

Some governments impose the levy by waste type (such as MSW, C&I waste and C&D waste) and some governments determine the levy by the waste composition like inert waste.
Landfill levy is the fee that is imposed by the government. Normally, the landfills will determine the landfill price according to the waste compositions.
Source: National waste report 2018 (pp 40-41)

Table A-7.2 Economic impacts contributions

Material	**Activity**	**Contribution**
C&D waste	Waste collection & Transportation & Pre-processing	52.1%
Masonry materials	Recycling (Masonry materials)	19.7%
	Landfilling (Masonry materials)	7.4%
Steel	Recycling (Steel)	8.3%
	Landfilling (Steel)	0.1%
Aluminium	Recycling (Aluminium)	1.8%
	Landfilling (Aluminium)	0.0%
Copper	Recycling (Copper)	2.9%
	Landfilling (Copper)	0.0%
Organics (Timber)	Recycling (Timber)	1.1%
	Landfilling (Timber)	0.8%
Paper & cardboard	Recycling (Paper & cardboard)	0.0%
	Landfilling (Paper & cardboard)	0.1%
Plastic	Recycling (Plastic)	0.0%
	Landfilling (Plastic)	0.2%
Glass	Recycling (Glass)	0.0%
	Landfilling (Glass)	0.0%
TLR	Recycling (TLR)	0.0%
	Landfilling (TLR)	0.0%
Others	Recycling (Others)	5.0%
	Landfilling (Others)	0.0%
Total		100.0%

Table A-7.3 (a) Economic impacts of Scenario I (unit: AUD)

Waste	**Activity**	**Scenario 1.1**	**Scenario 1.2**	**Scenario 1.3**	**Scenario 1.4**	**Scenario 1.5**
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.68E+09	1.68E+09	1.68E+09	1.68E+09	1.68E+09
Steel	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.05E+08	1.05E+08	1.05E+08	1.05E+08	1.05E+08

Aluminium	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	6.54E+06	6.54E+06	6.54E+06	6.54E+06	6.54E+06
Copper	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.96E+07	1.96E+07	1.96E+07	1.96E+07	1.96E+07
Organics (Timber)	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	9.77E+07	9.77E+07	9.77E+07	9.77E+07	9.77E+07
Paper & cardboard	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	9.65E+06	9.65E+06	9.65E+06	9.65E+06	9.65E+06
Plastic	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+07	1.30E+07	1.30E+07	1.30E+07	1.30E+07
Glass	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.65E+06	1.65E+06	1.65E+06	1.65E+06	1.65E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	2.60E+06	2.60E+06	2.60E+06	2.60E+06	2.60E+06
Others	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	7.82E+07	7.82E+07	7.82E+07	7.82E+07	7.82E+07
Total		5.63E+09	5.63E+09	5.63E+09	5.63E+09	5.63E+09

Table A-7.3 (b) Economic impacts of Scenario I (unit: AUD)

Waste	**Activity**	**Scenario 1.6**	**Scenario 1.7**	**Scenario 1.8**	**Scenario 1.9**	**Scenario 1.10**
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	4.94E+08	4.94E+08	4.94E+08	4.94E+08	4.94E+08
	Landfilling	1.26E+09	1.26E+09	1.26E+09	1.26E+09	1.26E+09
Steel	Recycling	1.57E+08	1.57E+08	1.57E+08	1.57E+08	1.57E+08
	Landfilling	7.84E+07	7.84E+07	7.84E+07	7.84E+07	7.84E+07
Aluminium	Recycling	3.43E+07	3.43E+07	3.43E+07	3.43E+07	3.43E+07
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06
Copper	Recycling	5.39E+07	5.39E+07	5.39E+07	5.39E+07	5.39E+07
	Landfilling	1.47E+07	1.47E+07	1.47E+07	1.47E+07	1.47E+07
Organics (Timber)	Recycling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
	Landfilling	7.32E+07	7.32E+07	7.32E+07	7.32E+07	7.32E+07
Paper & cardboard	Recycling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
	Landfilling	7.23E+06	7.23E+06	7.23E+06	7.23E+06	7.23E+06
Plastic	Recycling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
	Landfilling	9.76E+06	9.76E+06	9.76E+06	9.76E+06	9.76E+06
Glass	Recycling	4.95E+05	4.95E+05	4.95E+05	4.95E+05	4.95E+05
	Landfilling	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.95E+06	1.95E+06	1.95E+06	1.95E+06	1.95E+06
Others	Recycling	8.89E+07	8.89E+07	8.89E+07	8.89E+07	8.89E+07

	Landfilling	5.87E+07	5.87E+07	5.87E+07	5.87E+07	5.87E+07
Total		6.01E+09	6.01E+09	6.01E+09	6.01E+09	6.01E+09

Table A-7.3 (c) Economic impacts of Scenario I (unit: AUD)

Waste	**Activity**	**Scenario 1.11**	**Scenario 1.12**	**Scenario 1.13**	**Scenario 1.14**	**Scenario 1.15**
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	9.89E+08	9.89E+08	9.89E+08	9.89E+08	9.89E+08
	Landfilling	8.38E+08	8.38E+08	8.38E+08	8.38E+08	8.38E+08
Steel	Recycling	3.14E+08	3.14E+08	3.14E+08	3.14E+08	3.14E+08
	Landfilling	5.23E+07	5.23E+07	5.23E+07	5.23E+07	5.23E+07
Aluminium	Recycling	6.86E+07	6.86E+07	6.86E+07	6.86E+07	6.86E+07
	Landfilling	3.27E+06	3.27E+06	3.27E+06	3.27E+06	3.27E+06
Copper	Recycling	1.08E+08	1.08E+08	1.08E+08	1.08E+08	1.08E+08
	Landfilling	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06
Organics (Timber)	Recycling	9.77E+07	9.77E+07	9.77E+07	9.77E+07	9.77E+07
	Landfilling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
Paper & cardboard	Recycling	9.65E+06	9.65E+06	9.65E+06	9.65E+06	9.65E+06
	Landfilling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
Plastic	Recycling	1.30E+07	1.30E+07	1.30E+07	1.30E+07	1.30E+07
	Landfilling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
Glass	Recycling	9.90E+05	9.90E+05	9.90E+05	9.90E+05	9.90E+05
	Landfilling	8.25E+05	8.25E+05	8.25E+05	8.25E+05	8.25E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+06	1.30E+06	1.30E+06	1.30E+06	1.30E+06
Others	Recycling	1.78E+08	1.78E+08	1.78E+08	1.78E+08	1.78E+08
	Landfilling	3.91E+07	3.91E+07	3.91E+07	3.91E+07	3.91E+07
Total		6.40E+09	6.40E+09	6.40E+09	6.40E+09	6.40E+09

Table A-7.3 (d) Economic impacts of Scenario I (unit: AUD)

Waste	**Activity**	**Scenario 1.16**	**Scenario 1.17**	**Scenario 1.18**	**Scenario 1.19**	**Scenario 1.20**
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.48E+09	1.48E+09	1.48E+09	1.48E+09	1.48E+09
	Landfilling	4.19E+08	4.19E+08	4.19E+08	4.19E+08	4.19E+08
Steel	Recycling	4.71E+08	4.71E+08	4.71E+08	4.71E+08	4.71E+08
	Landfilling	2.61E+07	2.61E+07	2.61E+07	2.61E+07	2.61E+07
Aluminium	Recycling	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08
	Landfilling	1.63E+06	1.63E+06	1.63E+06	1.63E+06	1.63E+06
Copper	Recycling	1.62E+08	1.62E+08	1.62E+08	1.62E+08	1.62E+08
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06

Organics (Timber)	Recycling	1.46E+08	1.46E+08	1.46E+08	1.46E+08	1.46E+08
	Landfilling	2.44E+07	2.44E+07	2.44E+07	2.44E+07	2.44E+07
Paper & cardboard	Recycling	1.45E+07	1.45E+07	1.45E+07	1.45E+07	1.45E+07
	Landfilling	2.41E+06	2.41E+06	2.41E+06	2.41E+06	2.41E+06
Plastic	Recycling	1.95E+07	1.95E+07	1.95E+07	1.95E+07	1.95E+07
	Landfilling	3.25E+06	3.25E+06	3.25E+06	3.25E+06	3.25E+06
Glass	Recycling	1.48E+06	1.48E+06	1.48E+06	1.48E+06	1.48E+06
	Landfilling	4.12E+05	4.12E+05	4.12E+05	4.12E+05	4.12E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	6.50E+05	6.50E+05	6.50E+05	6.50E+05	6.50E+05
Others	Recycling	2.67E+08	2.67E+08	2.67E+08	2.67E+08	2.67E+08
	Landfilling	1.96E+07	1.96E+07	1.96E+07	1.96E+07	1.96E+07
Total		6.79E+09	6.79E+09	6.79E+09	6.79E+09	6.79E+09

Table A-7.3 (e) Economic impacts of Scenario I (unit: AUD)

Waste	Activity	Scenario 1.21	Scenario 1.22	Scenario 1.23	Scenario 1.24	Scenario 1.25
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.88E+09	1.88E+09	1.88E+09	1.88E+09	1.88E+09
	Landfilling	8.38E+07	8.38E+07	8.38E+07	8.38E+07	8.38E+07
Steel	Recycling	5.96E+08	5.96E+08	5.96E+08	5.96E+08	5.96E+08
	Landfilling	5.23E+06	5.23E+06	5.23E+06	5.23E+06	5.23E+06
Aluminium	Recycling	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08
	Landfilling	3.27E+05	3.27E+05	3.27E+05	3.27E+05	3.27E+05
Copper	Recycling	2.05E+08	2.05E+08	2.05E+08	2.05E+08	2.05E+08
	Landfilling	9.81E+05	9.81E+05	9.81E+05	9.81E+05	9.81E+05
Organics (Timber)	Recycling	1.86E+08	1.86E+08	1.86E+08	1.86E+08	1.86E+08
	Landfilling	4.88E+06	4.88E+06	4.88E+06	4.88E+06	4.88E+06
Paper & cardboard	Recycling	1.83E+07	1.83E+07	1.83E+07	1.83E+07	1.83E+07
	Landfilling	4.82E+05	4.82E+05	4.82E+05	4.82E+05	4.82E+05
Plastic	Recycling	2.47E+07	2.47E+07	2.47E+07	2.47E+07	2.47E+07
	Landfilling	6.51E+05	6.51E+05	6.51E+05	6.51E+05	6.51E+05
Glass	Recycling	1.88E+06	1.88E+06	1.88E+06	1.88E+06	1.88E+06
	Landfilling	8.25E+04	8.25E+04	8.25E+04	8.25E+04	8.25E+04
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05
Others	Recycling	3.38E+08	3.38E+08	3.38E+08	3.38E+08	3.38E+08
	Landfilling	3.91E+06	3.91E+06	3.91E+06	3.91E+06	3.91E+06
Total		7.10E+09	7.10E+09	7.10E+09	7.10E+09	7.10E+09

Table A-7.4(a) Economic impacts of Scenario II (unit: AUD)

Waste	Activity	Scenario 2.1	Scenario 2.2	Scenario 2.3	Scenario 2.4	Scenario 2.5
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.88E+09	1.88E+09	1.88E+09	1.88E+09	1.88E+09
	Landfilling	8.38E+07	8.38E+07	8.38E+07	8.38E+07	8.38E+07
Steel	Recycling	5.96E+08	5.96E+08	5.96E+08	5.96E+08	5.96E+08
	Landfilling	5.23E+06	5.23E+06	5.23E+06	5.23E+06	5.23E+06
Aluminium	Recycling	1.30E+08	1.30E+08	1.30E+08	1.30E+08	1.30E+08
	Landfilling	3.27E+05	3.27E+05	3.27E+05	3.27E+05	3.27E+05
Copper	Recycling	2.05E+08	2.05E+08	2.05E+08	2.05E+08	2.05E+08
	Landfilling	9.81E+05	9.81E+05	9.81E+05	9.81E+05	9.81E+05
Organics (Timber)	Recycling	1.86E+08	1.86E+08	1.86E+08	1.86E+08	1.86E+08
	Landfilling	4.88E+06	4.88E+06	4.88E+06	4.88E+06	4.88E+06
Paper & cardboard	Recycling	1.83E+07	1.83E+07	1.83E+07	1.83E+07	1.83E+07
	Landfilling	4.82E+05	4.82E+05	4.82E+05	4.82E+05	4.82E+05
Plastic	Recycling	2.47E+07	2.47E+07	2.47E+07	2.47E+07	2.47E+07
	Landfilling	6.51E+05	6.51E+05	6.51E+05	6.51E+05	6.51E+05
Glass	Recycling	1.88E+06	1.88E+06	1.88E+06	1.88E+06	1.88E+06
	Landfilling	8.25E+04	8.25E+04	8.25E+04	8.25E+04	8.25E+04
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05
Others	Recycling	3.38E+08	3.38E+08	3.38E+08	3.38E+08	3.38E+08
	Landfilling	3.91E+06	3.91E+06	3.91E+06	3.91E+06	3.91E+06
Total		7.10E+09	7.10E+09	7.10E+09	7.10E+09	7.10E+09

Table A-7.4 (b) Economic impacts of Scenario II (unit: AUD)

Waste	Activity	Scenario 2.6	Scenario 2.7	Scenario 2.8	Scenario 2.9	Scenario 2.10
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	1.48E+09	1.48E+09	1.48E+09	1.48E+09	1.48E+09
	Landfilling	4.19E+08	4.19E+08	4.19E+08	4.19E+08	4.19E+08
Steel	Recycling	4.71E+08	4.71E+08	4.71E+08	4.71E+08	4.71E+08
	Landfilling	2.61E+07	2.61E+07	2.61E+07	2.61E+07	2.61E+07
Aluminium	Recycling	1.03E+08	1.03E+08	1.03E+08	1.03E+08	1.03E+08
	Landfilling	1.63E+06	1.63E+06	1.63E+06	1.63E+06	1.63E+06
Copper	Recycling	1.62E+08	1.62E+08	1.62E+08	1.62E+08	1.62E+08
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06
Organics (Timber)	Recycling	1.46E+08	1.46E+08	1.46E+08	1.46E+08	1.46E+08
	Landfilling	2.44E+07	2.44E+07	2.44E+07	2.44E+07	2.44E+07
Paper & cardboard	Recycling	1.45E+07	1.45E+07	1.45E+07	1.45E+07	1.45E+07

	Landfilling	2.41E+06	2.41E+06	2.41E+06	2.41E+06	2.41E+06
Plastic	Recycling	1.95E+07	1.95E+07	1.95E+07	1.95E+07	1.95E+07
	Landfilling	3.25E+06	3.25E+06	3.25E+06	3.25E+06	3.25E+06
Glass	Recycling	1.48E+06	1.48E+06	1.48E+06	1.48E+06	1.48E+06
	Landfilling	4.12E+05	4.12E+05	4.12E+05	4.12E+05	4.12E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	6.50E+05	6.50E+05	6.50E+05	6.50E+05	6.50E+05
Others	Recycling	2.67E+08	2.67E+08	2.67E+08	2.67E+08	2.67E+08
	Landfilling	1.96E+07	1.96E+07	1.96E+07	1.96E+07	1.96E+07
Total		6.79E+09	6.79E+09	6.79E+09	6.79E+09	6.79E+09

Table A-7.4 (c) Economic impacts of Scenario II (unit: AUD)

Waste	Activity	Scenario 2.11	Scenario 2.12	Scenario 2.13	Scenario 2.14	Scenario 2.15
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	9.89E+08	9.89E+08	9.89E+08	9.89E+08	9.89E+08
	Landfilling	8.38E+08	8.38E+08	8.38E+08	8.38E+08	8.38E+08
Steel	Recycling	3.14E+08	3.14E+08	3.14E+08	3.14E+08	3.14E+08
	Landfilling	5.23E+07	5.23E+07	5.23E+07	5.23E+07	5.23E+07
Aluminium	Recycling	6.86E+07	6.86E+07	6.86E+07	6.86E+07	6.86E+07
	Landfilling	3.27E+06	3.27E+06	3.27E+06	3.27E+06	3.27E+06
Copper	Recycling	1.08E+08	1.08E+08	1.08E+08	1.08E+08	1.08E+08
	Landfilling	9.81E+06	9.81E+06	9.81E+06	9.81E+06	9.81E+06
Organics (Timber)	Recycling	9.77E+07	9.77E+07	9.77E+07	9.77E+07	9.77E+07
	Landfilling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
Paper & cardboard	Recycling	9.65E+06	9.65E+06	9.65E+06	9.65E+06	9.65E+06
	Landfilling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
Plastic	Recycling	1.30E+07	1.30E+07	1.30E+07	1.30E+07	1.30E+07
	Landfilling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
Glass	Recycling	9.90E+05	9.90E+05	9.90E+05	9.90E+05	9.90E+05
	Landfilling	8.25E+05	8.25E+05	8.25E+05	8.25E+05	8.25E+05
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.30E+06	1.30E+06	1.30E+06	1.30E+06	1.30E+06
Others	Recycling	1.78E+08	1.78E+08	1.78E+08	1.78E+08	1.78E+08
	Landfilling	3.91E+07	3.91E+07	3.91E+07	3.91E+07	3.91E+07
Total		6.40E+09	6.40E+09	6.40E+09	6.40E+09	6.40E+09

Table A-7.4 (d) Economic impacts of Scenario II (unit: AUD)

Waste	Activity	Scenario 2.16	Scenario 2.17	Scenario 2.18	Scenario 2.19	Scenario 2.20
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09

Masonry materials	Recycling	4.94E+08	4.94E+08	4.94E+08	4.94E+08	4.94E+08
	Landfilling	1.26E+09	1.26E+09	1.26E+09	1.26E+09	1.26E+09
Steel	Recycling	1.57E+08	1.57E+08	1.57E+08	1.57E+08	1.57E+08
	Landfilling	7.84E+07	7.84E+07	7.84E+07	7.84E+07	7.84E+07
Aluminium	Recycling	3.43E+07	3.43E+07	3.43E+07	3.43E+07	3.43E+07
	Landfilling	4.90E+06	4.90E+06	4.90E+06	4.90E+06	4.90E+06
Copper	Recycling	5.39E+07	5.39E+07	5.39E+07	5.39E+07	5.39E+07
	Landfilling	1.47E+07	1.47E+07	1.47E+07	1.47E+07	1.47E+07
Organics (Timber)	Recycling	4.88E+07	4.88E+07	4.88E+07	4.88E+07	4.88E+07
	Landfilling	7.32E+07	7.32E+07	7.32E+07	7.32E+07	7.32E+07
Paper & cardboard	Recycling	4.82E+06	4.82E+06	4.82E+06	4.82E+06	4.82E+06
	Landfilling	7.23E+06	7.23E+06	7.23E+06	7.23E+06	7.23E+06
Plastic	Recycling	6.51E+06	6.51E+06	6.51E+06	6.51E+06	6.51E+06
	Landfilling	9.76E+06	9.76E+06	9.76E+06	9.76E+06	9.76E+06
Glass	Recycling	4.95E+05	4.95E+05	4.95E+05	4.95E+05	4.95E+05
	Landfilling	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	1.95E+06	1.95E+06	1.95E+06	1.95E+06	1.95E+06
Others	Recycling	8.89E+07	8.89E+07	8.89E+07	8.89E+07	8.89E+07
	Landfilling	5.87E+07	5.87E+07	5.87E+07	5.87E+07	5.87E+07
Total		6.01E+09	6.01E+09	6.01E+09	6.01E+09	6.01E+09

Table A-7.4 (e) Economic impacts of Scenario II (unit: AUD)

Waste	Activity	Scenario 2.21	Scenario 2.22	Scenario 2.23	Scenario 2.24	Scenario 2.25
C&D waste	Waste collection and onsite sorting	3.62E+09	3.62E+09	3.62E+09	3.62E+09	3.62E+09
Masonry materials	Recycling	9.89E+07	9.89E+07	9.89E+07	9.89E+07	9.89E+07
	Landfilling	1.59E+09	1.59E+09	1.59E+09	1.59E+09	1.59E+09
Steel	Recycling	3.14E+07	3.14E+07	3.14E+07	3.14E+07	3.14E+07
	Landfilling	9.94E+07	9.94E+07	9.94E+07	9.94E+07	9.94E+07
Aluminium	Recycling	6.86E+06	6.86E+06	6.86E+06	6.86E+06	6.86E+06
	Landfilling	6.21E+06	6.21E+06	6.21E+06	6.21E+06	6.21E+06
Copper	Recycling	1.08E+07	1.08E+07	1.08E+07	1.08E+07	1.08E+07
	Landfilling	1.86E+07	1.86E+07	1.86E+07	1.86E+07	1.86E+07
Organics (Timber)	Recycling	9.77E+06	9.77E+06	9.77E+06	9.77E+06	9.77E+06
	Landfilling	9.28E+07	9.28E+07	9.28E+07	9.28E+07	9.28E+07
Paper & cardboard	Recycling	9.65E+05	9.65E+05	9.65E+05	9.65E+05	9.65E+05
	Landfilling	9.16E+06	9.16E+06	9.16E+06	9.16E+06	9.16E+06
Plastic	Recycling	1.30E+06	1.30E+06	1.30E+06	1.30E+06	1.30E+06
	Landfilling	1.24E+07	1.24E+07	1.24E+07	1.24E+07	1.24E+07
Glass	Recycling	9.90E+04	9.90E+04	9.90E+04	9.90E+04	9.90E+04

	Landfilling	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
TLR	Recycling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Landfilling	2.47E+06	2.47E+06	2.47E+06	2.47E+06	2.47E+06
Others	Recycling	1.78E+07	1.78E+07	1.78E+07	1.78E+07	1.78E+07
	Landfilling	7.43E+07	7.43E+07	7.43E+07	7.43E+07	7.43E+07
Total		5.70E+09	5.70E+09	5.70E+09	5.70E+09	5.70E+09

Appendix C: Published paper in *Resources, Conservation and Recycling*

Statement of Authorship

Title of Paper	Cross-regional mobility of construction and demolition waste in Australia: An exploratory study
Publication Status	[X] Published [ ] Accepted for Publication [ ] Submitted for Publication [ ] Unpublished and Unsubmitted work written in manuscript style
Publication Details	Wu, H., Zuo, J., Yuan, H., Zillante, G., & Wang, J. (2020). Cross-border regional mobility of construction and demolition waste in Australia: An exploratory study. *Resources, Conservation and Recycling*, 156, 104710. https://doi.org/10.1016/j.resconrec.2020.104710.

Principal Author

Name of Principal Author (Candidate)	Huanyu Wu		
Contribution to the Paper	Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft		
Overall percentage (%)	60%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	05/05/2020

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Jian Zuo		
Contribution to the Paper	Supervision, Conceptualisation, Methodology, Writing - review & editing, Validation		
Signature		Date	7/5/2020

Name of Co-Author	Hongping Yuan		
Contribution to the Paper	Visualisation, Methodology, Writing - review & editing		
Signature		Date	07/05/2020

Name of Co-Author	George Zillante		
Contribution to the Paper	Supervision, Writing - review & editing		
Signature		Date	7/5/2020

Name of Co-Author	Jiayuan Wang		
Contribution to the Paper	Supervision, Writing – review & editing		
Signature		Date	07/05/2020

Resources, Conservation & Recycling 156 (2020) 104710

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Cross-regional mobility of construction and demolition waste in Australia: An exploratory study

Huanyu Wu[a], Jian Zuo[a,b,*], Hongping Yuan[c], George Zillante[a], Jiayuan Wang[b]

[a] *School of Architecture and Built Environment, The University of Adelaide, SA, 5001, Australia*
[b] *College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, 518060, PR China*
[c] *School of Management, Guangzhou University, Guangzhou, Guangdong, 510006, PR China*

ARTICLE INFO

Keywords:
C&D waste
Waste management
Cross-Regional mobility
Performance
Australia

ABSTRACT

Construction and demolition (C&D) waste has become one of the most significant waste streams and many countries are seeking to promote the waste recycling rate. Due to heavyweight, low unit economic value, and legislation requirements, C&D waste is normally managed locally. According to the *National Waste Reports* in Australia, over the past few years some C&D waste materials have been transported from the originally generated region to other regions for further treatment. The cross-regional mobility of C&D waste will affect the quantity of waste in the regional waste management system, which brings environmental, economic and social impacts on the system. By employing methods of site surveys, expert interviews, expert seminars and desktop surveys, this study aims to understand the C&D waste treatment and management particularly the cross-regional mobility of the waste in Australia. Firstly, the compositions and generation of C&D waste in Australia are investigated while strategies are provided for managing the waste. Secondly, the flows of C&D waste in the country are mapped, among which the waste cross-regional mobility map in Australia reveals significant information such as the states and territories involving in the waste cross-regional mobility, the waste mobility routes, and transported waste materials. Accordingly, the characteristics of C&D waste in Australia are discussed. Similarly, the causes and impacts of cross-regional mobility of C&D waste are analysed. The findings of the study help gain insights of C&D waste management in Australia, which is valuable for other countries or regions to improve their waste management performance. In addition, the study would also enrich existing C&D waste management theory by adding the cross-regional mobility issues.

1. Introduction

Construction and demolition (C&D) waste has become one of the most significant streams of solid waste around the globe (Wu et al., 2019a, 2019b). The composition of C&D waste mainly includes masonry waste (such as asphalt, concrete, bricks, and plasterboard), metals (such as aluminium, steel, etc.), organics (such as timber and other garden organics), plastics, glass, paper & cardboard, TLR (Textiles, leather and rubber), and others (Department of the Environment and Energy, DoEE, 2018). Except some harmful matters and mixed waste fragments, the majority of C&D waste materials could be recycled or be energy recovered (European Commission, 2019). According to the *Australia National Waste Report 2018*, the general recycling rate of C&D waste in the country is about 67 %, while the recycling performance is much better in some Australian states and territories. For instance, the diversion rate (including recycling and energy recovery) of C&D waste in South Australia has reached 91 % in 2018 (Green Industries SA, GISA, 2019), and the recycling rate of the waste in New South Wales has achieved 81 % in 2017 (NSW EPA, 2019b). Australia's recycling rate of C&D waste is higher than other developed regions or countries such as the US (45 %) and Norway (41 %) (Department of the Environment and Energy, DoEE, 2018). It has been reported that the recycling performance of C&D waste in Australia is higher than many developing regions where the most part of C&D waste has been

Acronyms: ACT, Australian Capital Territory; AUD, Australian Dollar; C&D waste, Construction and demolition waste; C&I waste, Commercial and industrial waste; DoEE, Department of the Environment and Energy; EC, European Commission; EPA, Environmental Protection Agency; GIS, Geographic information system; GISA, Green Industries SA; HKU, Hongkong University; MAF, Material Flow Analysis; MSW, Municipal Solid Waste; NSW, New South Wales; NT, Northern Territory; QG, Queensland Government; QLD, Queensland; SA, South Australia; SV, Sustainability Victoria; TAS, Tasmania; TLR, Textiles, leather and rubber; US, United States; VIC, Victoria; WA, Western Australia

* Corresponding author at:School of Architecture and Built Environment, The University of Adelaide, Room 472, SA, 5001, Australia.
E-mail address: jian.zuo@adelaide.edu.au (J. Zuo).

https://doi.org/10.1016/j.resconrec.2020.104710
Received 2 November 2019; Received in revised form 14 January 2020; Accepted 14 January 2020
Available online 22 January 2020
0921-3449/

disposed of in landfills (Wang et al., 2019; Yuan and Yang, 2020; Ajayi et al., 2016; Esa et al., 2017). Hence, the Australian experience in managing C&D waste could provide valuable information for other countries that are seeking to improve their waste management performance (Udawatta et al., 2015; Stephan and Athanassiadis, 2018).

Benefits associated with C&D waste management are obvious, such as avoiding the landfilling, reducing the demand of raw materials, and minimising adverse environmental impacts (Lu et al., 2015, 2016). A large amount of studies have been conducted from the management perspective (Hu et al., 2010; Blengini and Garbarino, 2010; Wiedenhofer et al., 2015; Stephan and Athanassiadis, 2018; Liu et al., 2019; Miatto et al., 2019), such as examining waste management practices, investigating material flows, and evaluating waste management performance (Yeheyis et al., 2013; Lu and Yuan, 2010; Li et al., 2018a, b; Wu et al., 2019a). According to these studies, it is necessary to consider C&D waste management as a system (Dosho, 2007; Yuan and Wang, 2014). Since the large portion of C&D waste is contributed by materials that are heavy and low value, the transportation of waste is normally of low-level efficiency (Solís-Guzmán et al., 2009; Coelho and de Brito, 2011; Miatto et al., 2019). Meanwhile, C&D waste is generally managed by local authorities in some countries. The waste is normally expected to be treated and recycled at local recycling facilities or disposed of at local landfills (Wiedenhofer et al., 2015; Stephan and Athanassiadis, 2018; Miatto et al., 2019). Therefore, the management of C&D waste is usually viewed as local-closed issues, and the system boundary has been limited at the regional level (Wu et al., 2019b).

In fact, driven by various factors such as facility availability, regulations, economic incentive and industry common practices, it has been reported that C&D waste were transported from the originally generated region to other regions for further treatment in some countries (Department of the Environment and Energy, DoEE (2018); Sustainability Victoria, SV, 2017; NSW EPA, 2019a; Queensland Government, QG, 2018; Green Industries SA, GISA, 2019). For instance, a large amount of C&D waste has been transported from New South Wales (NSW, a state in Australia) to Queensland (QLD, a state in Australia) for landfilling, as a response to the significant difference on recycling and disposal cost among regions (Department of the Environment and Energy, DoEE, 2018). Academic institutions in China are promoting the cross-regional mobility of C&D waste in the Greater Bay Area (HKU, 2019). The cross-regional mobility of C&D waste will affect the quantity of waste in the regional waste management system, which will further affect the environmental, economic and social performance of the system (Sustainability Victoria, SV, 2017). Therefore, it is necessary to rethink the system boundary of C&D waste management and investigate the cross-regional mobility of C&D waste. This will help to better understand the drivers to optimise the waste management system for improving management efficiency. However, very few studies have attempted to examine the cross-regional mobility issues in C&D waste management.

Therefore, the study aims to understand: (1) the current status of C&D waste management, particularly the cross-regional mobility issues of the waste in Australia, and (2) what are the drivers and impacts of the cross-regional mobility of C&D waste.

2. Literature review

2.1. Generation and flows of C&D waste

Many studies have attempted to investigate C&D waste generation during the last two decades, because the waste generation data forms the fundamental information for planning waste management facilities.

The first cluster of C&D waste research mainly focuses on three aspects. For instance, some studies focus on investigating waste generation rates of different materials (Lu et al., 2016; Li et al., 2018b; Mália et al., 2013; Lu et al., 2016). Multiple methods such as site visit, questionnaire, expert interview and desktop survey were adopted in such studies to obtain the data for estimating waste generation (Wu et al., 2014).

The second cluster concentrates on investigating C&D waste generation according to types of projects. Typically, the C&D waste generation for a building can be calculated by multiplying the waste generation rates and the gross floor area (Saez and Del Rio, 2011; Solís-Guzmán et al., 2009; Mercader-Moyano et al., 2013). Apart from this, many studies have been conducted to investigate C&D waste generation in specific countries/regions, such as Norway (Bergsdal et al., 2007a, b), Spain (Solís-Guzmán et al., 2009), Portugal (Coelho and de Brito, 2011), Italy (Miatto et al., 2019), USA (Cochran et al., 2007), Malaysia (Lau et al., 2008), and China (Zheng et al., 2017; Wu et al., 2016a). However, there is very limited studies of Oceania found in international journals (Udawatta et al., 2015; Stephan and Athanassiadis, 2018). Hence, investigating C&D waste generation in Australia can add the knowledge in the area.

The third cluster concentrates on tracking material flows of C&D waste in order to understand the materials that flow from waste generation to its final disposal (Hu et al., 2010; Blengini and Garbarino, 2010; Wiedenhofer et al., 2015; Stephan and Athanassiadis, 2018; Miatto et al., 2019). Consequently, measures could be introduced to minimise the waste generation and reduce the waste being disposed of in landfills (Wu et al., 2019a). For instance, Tanikawa and Hashimoto (2009) adopted a 4D-GIS approach to analyse the spatial material stock in urban areas in UK and Japan. By adopting a dynamic material flow approach, Hu et al. (2010) analysed the C&D waste generated in the urban housing system in Beijing, China and evaluated the environmental impacts of the waste. Based on the GIS approach, Wu et al. (2016b) conducted the spatial analysis of the generation, recycling and disposal of C&D waste in Shenzhen, China. Apart from the European studies above, Blengini and Garbarino (2010) investigated the recycling chain of C&D waste in Italy. Miatto et al. (2019) calculated the total material stock and demolition waste flows for Padua in Italy for the period 1902–2007. However, comprehensive maps have not been developed to illustrate the processing and disposal of C&D waste (Blengini and Garbarino, 2010; Wiedenhofer et al., 2015). The reason lies in that C&D waste flows involve multiple stages and destinations and effective approaches of collecting waste flow data are lacking (Bergsdal et al., 2007a; Coelho and de Brito, 2011; Wu et al., 2019b). Therefore, hybrid approaches can be employed to collect broader and more comprehensive fundamental data (e.g. the site visit, questionnaire, expert interview and desktop survey) (Wu et al., 2014). This can enrich the methods regarding the characteristics of materials flows.

2.2. The cross-regional mobility issues

The concept of cross-regional mobility has been examined in many disciplines. It usually refers to people or items moving cross the administrative boundaries to seek an optimised outcome. For instance, Song et al. (2003) studied the patenting activities of engineers who relocated from the US companies to non-U.S. companies. In the innovation management field, Singh (2008) investigated the relationships among the distributed research and development, quality of innovative output, and the cross-regional knowledge integration by analysing the patents from different firms. Miguélez and Moreno (2015) particularly looked at the interactions between cross-regional mobility, regions' absorptive capacity and networks. In the finance field, Chan et al. (2011) examined the cross-region mobility of capital in China and tracked the changes of mobility degree over time. In human migration studies, Saarivirta and Consoli (2014) focused on the established universities and graduate mobility in Finland and Alexeev and Chernyavskiy (2018) assessed the regional economies and the federal transfers in Russia in 2009–2015. In the environmental area, Heininen (2005) investigates the impacts of the globalization and climate change on Circumpolar North by adopting the cross-regional mobility concept. However, the cross-regional mobility concept has been rarely mentioned in construction-related research excepted one research by Li et al. (2018c) studying the cross-regional mobility of wood materials for construction. In the above studies, it is found that cross-regional mobility can optimise the redistribution of resources. However, it is also reported that its potential impacts on the balance of the system should not be overlooked.

Previously the waste is usually viewed as local-closed issues and the system boundary has been limited at the regional level. Recently a few studies reported the cross-regional mobility issues of C&D waste (Li et al., 2018c; Wu et al., 2019b). Driven by factors such as the economic incentive and the availability of recycling facilities, C&D waste has been transported from the originally generated region to other regions for further treatment (Department of the Environment and Energy, DoEE, 2018; Queensland Government, QG (2018); NSW EPA, 2019a; Sustainability Victoria, SV, 2017, 2018a). However, very few studies have attempted to investigate cross-regional mobility issues associated with C&D waste in Australia. Hence, studying the cross-regional mobility of C&D waste can expand the system boundary of C&D waste management and better understand the impacts of C&D waste. Changing the perspective from the local-closed to the cross-regional mobility can also contribute to the advancement of C&D waste research.

3. Methodology

The aim of the study is to understand the C&D waste treatment and management particularly the cross-regional mobility of the waste in Australia. It concentrates on the C&D waste generated in Australia, which covers eight Australian states and territories, including "Australian Capital Territory (ACT), New South Wales (NSW), Northern Territory (NT), Queensland (QLD), South Australia (SA), Tasmania (TAS), Victoria (VIC), and Western Australia (WA)". To achieve the aim, a research framework is developed (Fig. 1).

3.1. Investigating the treatment and management of C&D waste in Australia

Considering this study includes both qualitative and quantitative information, the data were collected by a hybrid approach including site surveys, experts seminar, experts interview and desktop survey (see Section 3.3).

To be specific, the desktop survey (namely the contents analysis focusing on the selected reports) was conducted to obtain a list of main compositions of C&D waste generated in Australia, and to quantify the percentages of C&D waste that flowed to different destinations such as recycling operations, organic processing operations, landfills, and illegal dumpings.

As treatment and management of C&D waste are very complex and the scenarios are different from case to case. A single method cannot obtain comprehensive information to draw a whole picture for C&D waste management. To gain an in-depth understanding of the issue, a series of site surveys, experts seminar, experts interviews were conducted to identify the flows and life cycle procedure (i.e., the waste processing) of C&D waste in Australia.

3.2. Investigating the cross-regional mobility of C&D waste of Australia

To investigating the cross-regional mobility of C&D waste in Australia, three steps were designed: *a)*. developing a conceptual model of C&D waste cross-regional mobility; *b)*. quantifying C&D waste cross-regional mobility in Australia; and *c)*. mapping the waste cross-regional mobility in Australia.

Step 1: Developing a conceptual model of C&D waste cross-regional mobility

The terminology of "C&D waste cross-regional mobility" means moving C&D waste across the state or country borders, for example, some C&D wastes are transported across borders to be processed or dumped in other regions. The concept of C&D waste cross-regional mobility is proposed to compare to the intra-regional mobility (i.e., processing the waste at local facilities). Based on the interview with C&D waste management experts in Australia (Please see Section 3.3.1), a conceptual model is developed to present the phenomenon of C&D waste cross-regional mobility (Fig. 2). After the generation of C&D waste, the waste will be collected and initially sorted on-site. Normally, the managed waste will be transported to be pre-processed (i.e., sorting); while some unmanaged C&D waste may be dumped illegally. After the pre-processing, apart from being processed intra-regional (Local), C&D waste can be transported across the border and treated in other regions (Interstates) or be transported to other countries (Overseas) for further processing (i.e., recycling, energy recovery, and landfilling).

Step 2: Quantifying C&D waste cross-regional mobility in Australia

The quantification of the amount of bulk forms essential part of a material flow analysis (Bringezu and Moriguchi 2002). The first task is

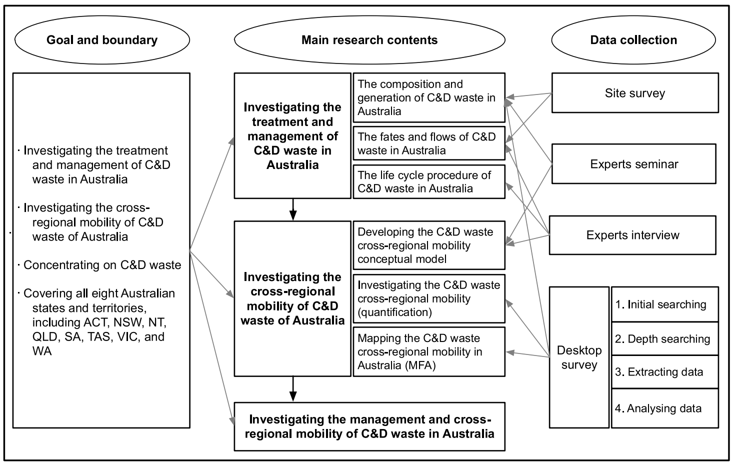


Fig. 1. The research framework.

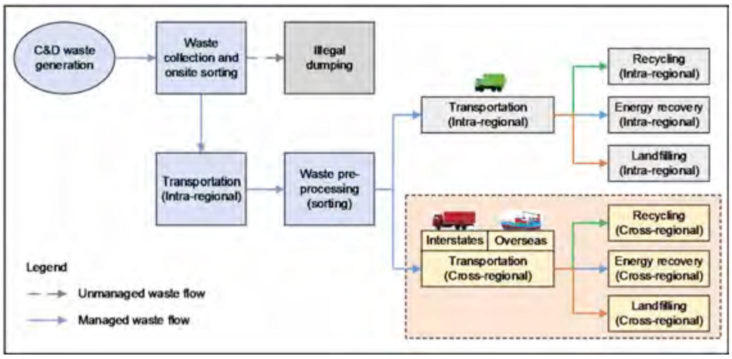


Fig. 2. The C&D waste cross-regional mobility conceptual model *C&D waste generation trend and fates; (b) The compositions of C&D waste. Data extracted from Australia National Waste Report 2018 database* (DoEE, 2018).

to identify categories of C&D waste involved in the cross-regional mobility network. Specifically, it is imperative to investigate what categories of C&D waste are transported across regions and treated in regions different from the original generation region, and accordingly to quantify the volumes for these wastes. According to Australia's National Waste Report 2018, the core compositions of C&D waste consists of eight categories: "C1-Masonry materials (including asphalt, bricks, concrete, and plasterboard & cement sheeting), C2-Metals (including steel, aluminium, and non-ferrous metals), C3-Organics (including garden organics and timber), C4-Paper & cardboard, C5-Plastics, C6-Glass, C7-Textiles, leather & rubber, and C8-other" (Department of the Environment and Energy, DoEE, 2018).

The second task is to quantify the amount of waste in each category involved in the cross-regional mobility network. Based on the cross-regional mobility conceptual model and the core waste compositions, a quantification model is developed via the Excel for quantifying the C&D waste cross-regional mobility in Australia. The quantification model includes a number of datasets such as the original waste generation region, the terminal waste cross-regional mobility region, waste category, and the amount of waste involving waste cross-regional mobility. A desktop survey (see section 3.3.2) was conducted to obtain the data to input in the quantification model.

Step 3: Mapping the waste cross-regional mobility in Australia

To map the cross-regional mobility of C&D waste in Australia, Material Flow Analysis (MFA) method is applied in the study. MFA provides an effective tool to "quantify flows and stocks of materials or substances in a well-defined system" (Bringezu & Moriguchi 2002). This method has been used in quantifying the generation of C&D waste in certain areas in previous studies (Shen et al., 2004; Wu et al., 2017). The MFA methods in previous studies were mainly conducted in a local-closed boundary, which is determined by their research aims. As the research goal in this study is to examine the cross-regional mobility of C&D waste, it is necessary to improve the traditional MFA method accordingly to match the research questions. One of the improvements of the MFA method in this study is to take the geographic mobility of C&D waste into consideration. The implication of the MFA in mapping the cross-regional mobility of C&D waste in Australia is shown in Fig. 5 in section 4.2.

3.3. Data collection and data sources

The data collection approaches consist of two aspects: acquiring qualitative data by site surveys expert seminar and expert interview; and collecting quantitative data by desktop survey.

3.3.1. Site surveys, experts seminar and experts interviews

To investigate the compositions and flows of C&D waste in Australia, a series of site surveys, expert seminar and expert interviews were conducted from November 2018 to July 2019. The site surveys include three high-rise apartment projects, an aged care project, two school redevelopment projects, a hospital reconstruction project, one railway station reconstruction project and two waste recycling centres. The expert seminar was hosted on May 30, 2019. Attendees included three C&D waste recyclers, two building components suppliers, three constructors/builders, one waste management related government officer and an academic. These were followed by the site surveys on two C&D waste recycling centres, two expert interviews with the senior managers of major C&D waste recyclers in South Australia in July 2019. Table 1 and Table 2 list the information of the site surveys, expert seminar and expert interview.

3.3.2. Desktop survey

A desktop survey was conducted to investigate C&D waste generation and cross-regional mobility in Australia. Firstly, an initial search was conducted in November 2018 to identify main data sources that are available to the public domain. Secondly, an in-depth search was conducted with websites of Australian governments, industry associations and professional bodies to download related reports with contents of C

Table 1
Information of the site surveys.

Activity	Organisation/construction type	Number	Date
Site survey	Construction/demolition site — high-rise apartments	3	Nov, Dec-2018
	Construction/demolition site — aged care project	1	Apr-2019
	Construction/demolition site — school project	2	Apr-2019
	Construction/demolition site — hospital	1	Jun-2019
	Construction/demolition site — railway station	1	May-2019
	C&D waste recycling centre	2	Jul-2019

Table 2
Information of expert seminar and expert interview.

Activity	Organisation/expert type	Working experience (year)	Date
Expert seminar	C&D waste recycler 1	20	May-2019
	C&D waste recycler 2	13	
	C&D waste recycler 3	8	
	Building components supplier 1	11	
	Building components supplier 2	6	
	Constructor/builder 1	15	
	Constructor/builder 2	12	
	Constructor/builder 3	8	
	Government officer (C&D waste management related)	20	
	Academic	30	
Expert interview	Senior manager of renowned C&D waste recycler 1	20	Jul-2019
	Senior manager of renowned C&D waste recycler 2	13	

&D waste information (see Table 3). Thirdly, the data were exacted and analysed from December 2018 to March 2019, according to the requirements developed in Section 3.1 and Section 3.2. The data exaction was based on the contents analysis of the selected reports. The data exaction and analysis took significant time because the data structure in some data sources is very complex. Some data were combined with data of commercial and industrial (C&I) waste, municipal solid waste (MSW), and construction and demolition (C&D) waste, which need to be identified and separated carefully. As there are no available data in the specific waste report for North Territory and Tasmania, the related data reported in *National Waste Report 2018* and the database of *National Waste report 2018* were used for these two regions. This was considered acceptable, as the weight of C&D waste generation of these two regions accounts for less than 1 % of the total C&D waste generation in the entire country.

4. Results

4.1. The treatment and management of C&D waste in Australia

4.1.1. C&D waste compositions and generation in Australia

Based on the data extracted from *National Waste Report 2018 – Database*, the C&D waste generated in 2017 is 20.4 million tonnes, which includes about 13.6 million tonnes of C&D waste been recycled, about 6.7 million tonnes been disposed of in landfills, and about 0.1 million tonnes been energy recovered (Department of the Environment and Energy, DoEE, 2018). As shown in Fig. 3(a), the generation of C&D waste increased steadily in the last decade from about 17 million tonnes in 2007 to more than 20 million tonnes in 2016 and 2017. Meanwhile, the amount of recycled waste also increased in the survey period. From the perspective of percentages, more than 60 % of C&D waste in Australia has been recycled and around 40 % of the waste was sent to landfills, where some minor materials have been energy recovered. The waste recycling rate in Australia shows an increasing trend, which has increased steadily from 60 % in 2007 to 67 % in 2017.

In regards to the waste compositions by weight, about 83 % of generated waste in Australia is masonry materials, followed by 6 % metal waste and 5 % organics waste (mainly timber). The percentages of wastes (by weight) such as plastics, paper & cardboard, glass, TLR (textiles, leather & rubber) are not significant, contributing less than 1 % each. The rest cannot be sorted or classified (Fig. 3(b)).

4.1.2. The fates and flows of C&D waste in Australia

Regarding the fates of C&D waste compositions in Australia, about 90 % of metals have been recycled, followed by about 80 % of glass and 70 % of masonry materials recycled. According to the Senior manager of renowned C&D waste recycler 1 in SA in the expert interview "*95 % of recyclable waste can be recycled if the waste materials have been distributed into the recycling facilities, however, there is a considerable amount of C&D waste has been transported into landfills.*". Hence, although the recycling rates of C&D waste such as masonry materials, metals and glass are competitively high, there are significant percentages of some waste compositions being transported to landfills, such as organics, paper & cardboard, plastics, textiles, leather & rubber. Meanwhile, the overall percentage of C&D waste being energy recovered is minor.

Based on the compositions and fates of C&D waste data extracted and processed from the *National Waste Report 2018 – Database,* and the site surveys of two "C&D waste recycling centres" in SA and the interviews on the "senior managers" of two renowned C&D waste recycler in SA, the C&D waste flows in Australia are illustrated in Table 4. A diagram for the C&D waste flows in Australia is developed in Fig. 4. It shows that there are three main C&D waste infrastructure types including waste recycling operations, organic processing operations, and landfills. Apart from these C&D waste infrastructure, there is still some C&D waste being dumped illegally according to the "senior manager of renowned C&D waste recycler 1 and 2 in SA", which is consistent with the information revealed in the *National Waste Report 2018* (Department of the Environment and Energy, DoEE, 2018).

After the waste recycling operations, the majority of masonry waste is recycled into aggregates mainly for road base, concrete, etc. Some waste compositions such as metal, paper, glass, plastic have been sorted and classified for further remanufacturing. Some combustible waste compositions such as organics (mainly timber), paper & cardboard, and textiles, leather & rubber (excl. tires) can be made into alternative fuel for energy recovery, i.e., waste to energy. Some waste components can be made for land rehabilitation, soil improvement, and urban development. Meanwhile, some sorted organic compositions will be sent to

Table 3
Selected waste reports for desktop survey.

Region	Report name	Source
National	*National Waste Report 2018*, National Waste report 2018 - database	(Department of the Environment and Energy, 2018)
ACT	*Waste Feasibility Study - Roadmap and Recommendations 2018*	(ACT Government, 2018)
VIC	*State-wide Waste and Resource Recovery Infrastructure Plan (Victoria 2017)*	(Sustainability Victoria, SV, 2018a)
	Victorian Recycling industry Annual Report 2015 - 2016	(Sustainability Victoria, SV, 2017)
	Victorian Recycling industry Annual Report 2016 - 2017	(Sustainability Victoria, SV, 2018b)
NSW	*Waste and Resource Recovery Infrastructure Needs Report 2017-21*	(NSW EPA, 2019a)
	Waste Avoidance and Resource Recovery Strategy Progress Report 2017-18	(NSW EPA, 2019b)
QLD	*Recycling and Waste in Queensland 2018 report*	Queensland Government, QG (2018)
	Transforming Queensland's Recycling and Waste Industry Directions Paper	Queensland Government, QG (2019)
SA	*South Australia's Recycling Activity Survey 2017-18 Report*	GISA (2019)
WA	*Recycling activity in Western Australia 2016 - 2017*	Waste Authority, WA (2018)
NT	*National Waste Report 2018; National Waste report 2018 - database*	(Department of the Environment and Energy, DoEE (2018)
TAS	*National Waste Report 2018; National Waste report 2018 - database*	(Department of the Environment and Energy, DoEE (2018)

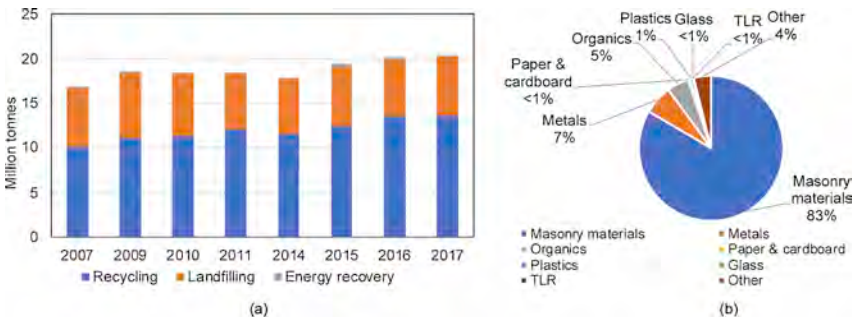


Fig. 3. Generation, fates and compositions of C&D waste in Australia (2007–2017) *Note: - All pictures were taken during the site surveys in Adelaide. - The waste flow data were extracted and processed from the National Waste Report 2018 – Database.The waste flow diagram was refined with the help of a manager of a renowned C&D waste recycler.*

the organic processing operations and the rest of the unrecyclable waste disposed of in landfills.

There are some organic C&D waste materials such as timber and garden waste being transported to the organic processing operations directly from the construction or demolition sites. In the organic processing operations, the waste will be made for land rehabilitation, soil improvement, and urban development, and some combustible waste can be made into alternative fuel for energy recovery. The unrecyclable waste materials will be disposed of in landfills. While in some situations, some recyclable waste materials sorted out in the organic processing operations will be transported to waste recycling operations.

4.2. C&D waste cross-regional mobility in Australia

Although the majority of the C&D waste by weight is processed within the region, it is found that some of the waste is generated in one state but transferred to another (Department of the Environment and Energy, DoEE, 2018). Typically, the national waste report and the states/territories only report the waste that is managed within their boundaries but based on the in-depth survey (Discussed in section 3.2.2), some of the C&D waste cross-regional mobility can be revealed. There are three main forms of waste cross-regional mobility in Australia, i.e., transport to interstates for recycling, transport to interstates for landfilling, and export to overseas for reprocessing/recycling. Normally, the recyclable materials after reprocessing will be further recycled. A map is developed to illustrate the waste cross-regional mobility in Australia (Fig. 5). The data for producing the map is shown in Table 5.

4.2.1. Transport to interstates for recycling

The results show that South Australia (SA) is at the centre of waste cross-regional mobility for reprocessing/recycling in Australia. Many states or territories transport their waste to this state for reprocessing/recycling. For instance, SA received some metals and glass from the North Territory. It received metals, plastics, and glass from New South Wales. Apart from this, the state also received about 2237 tons of metals (2 %). 11 tons of paper & cardboard (< 1 %), and some glass form Western Australia. Meanwhile, it is found that SA transports about 14,981 tons of metals (48 %), 1954 tons of plastics (48 %) of recovered C&D waste to interstates for recycling (Green Industries SA, GISA, 2019). This is mainly because some parties in the supply chain would choose to trade the material to wherever the best economic benefits can be gained.

It is found that Victoria (VIC) transports 32,985 tons of metals (25 %), 2374 tons of paper & cardboard (46 %), 2074 tons of plastic (74 %), 445 tons of TLR (45 %), 75 tons of glass (7 %), and 656 tons of organics (1 %) of recovered C&D waste to interstates or overseas for reprocessing/recycling (Sustainability Victoria, SV, 2017; Sustainability Victoria, SV, 2018b), based on an examination of related information from multiple reports (such as the *National Waste Report 2018*; *Victorian Recycling Industry Annual Report 2016 - 17*; *State-wide Waste and Resource Recovery Infrastructure Plan (Victoria 2017)*; and *South Australia's Recycling Activity Survey 2017-18 Report*). The destination of these waste materials originally generated in Victoria is most likely SA.

The results also show that Queensland (QLD) transports a minor amount of masonry materials, which is about 243 tons (< 0.1 %), 64,516 tons of metals (26 %), 71 tons plastics (33 %), 53 t TLR (< 1 %) of recovered waste to interstates for recycling (Queensland Government, QG, 2018); however, it was unable to identify the destinations of these waste due to a lack of data. According to Queensland Government 2018, "organic wastes and masonry materials were recovered in QLD, while the most of metals, paper & cardboard, and plastics were transported to interstates or overseas for further recovery" (Queensland Government, QG, 2018).

4.2.2. Transport to interstates for landfilling

As the C&D waste flows are likely managed by commercial service providers, destinations will change in response to changes in gate fees

Table 4
The C&D waste flows in Australia.

Source stream	Percentage	Waste infrastructure	Percentage	Recycled products
C&D waste	100 %	C&D waste recycling operations	66 %	Recycled aggregate (road base) Remanufacturing of paper, metal, glass, plastic, rubber, etc.
		Organic processing operations	< 1 %	Land rehabilitation, agriculture, soil improvement and urban development Alternative fuel (waste-to-energy)
		C&D waste landfills	32 %	–
		Illegal dumping	< 1 %	–

Note:- The recycled products of land rehabilitation, agriculture, soil improvement and urban development, and alternative fuel (waste-to-energy) are also produced from the C&D waste recycling operations.- The data are extracted from the national waste report 2018 – database.

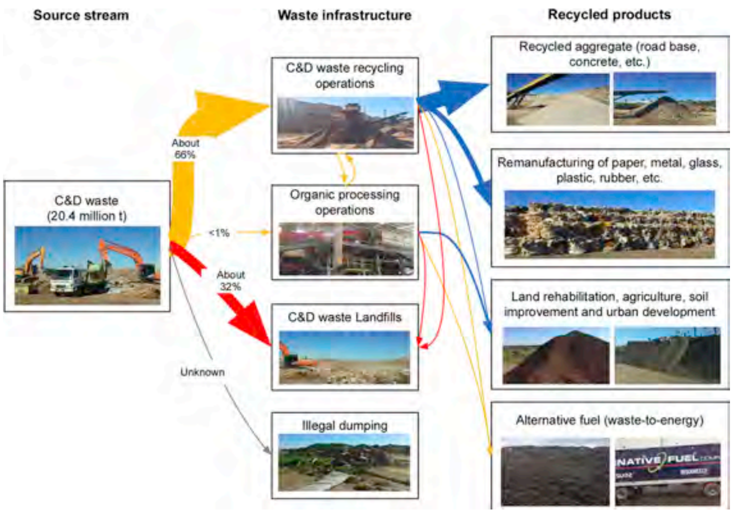


Fig. 4. C&D waste flows in Australia.

at reprocessors and landfills (Department of the Environment and Energy, DoEE, 2018). Therefore, some masonry will be transported cross-border to be disposed of in landfills where it has lower disposal fee or even no disposal fee applied. This is more likely the case in the eastern regions of Australia, where these states or territories share the border and stand closer but the disposal fees are dramatically different.

It is found that some masonry waste (16,000 tons) originally generated in the north part of VIC has been transported to New South Wales (NSW) for landfilling in 2016; at the same time, about 68,000 tons of masonry waste from NSW was transported to landfills in the northeast region of VIC (Sustainability Victoria, SV, 2017; Department of the Environment and Energy, DoEE, 2018). This kind of waste "exchange" also took place between NSW and the Australia Capital Territory (ACT). The results show that 561,118 tons of Queanbeyan landfilling C&D waste in NSW were sent to the ACT for re-landfilling (Queensland Government, QG, 2018); meanwhile, some masonry wastes originally generated in ACT were transported to NSW for landfilling due to shorter transportation distance and exceptional no disposal fee applied. Apart from this, according to the *National Waste Report 2018* database, NSW also transported about 639,747 tons of masonry waste to QLD for landfilling disposal.

4.2.3. Transport to overseas for reprocessing/recycling

As some C&D waste materials (such as metals, plastics, and paper & cardboard) are involved in the global trade networks, these recovered materials will be transported to wherever there is a market and the best economic benefits can be achieved. According to the "senior manager of renowned C&D waste recycler 2 in SA", with the same category of materials generated from other sectors (such as commercial and industrial waste sector, municipal solid waste sector), some of these

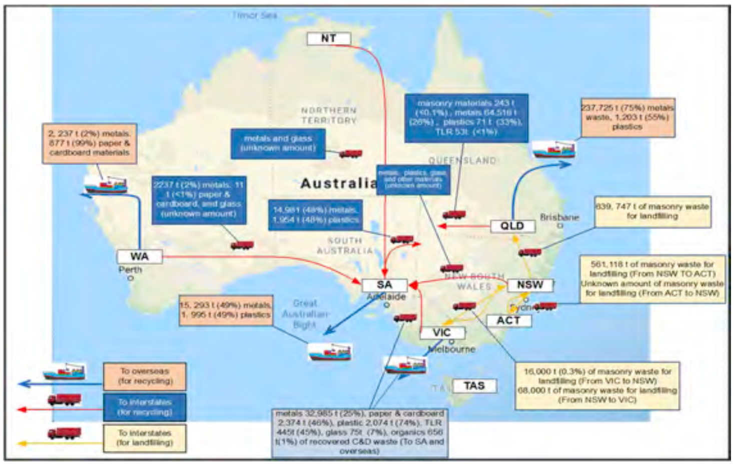


Fig. 5. The C&D waste cross-regional mobility map of Australia.

Table 5
Australian C&D waste cross-regional mobility.

Origin	Destination	C&D waste materials	Treatment and disposal	Notes
Interstates cross-regional mobility				
VIC	NSW	16,000 t (0.3 %) of masonry waste	landfilling	Cross-border and export flows data extracted from *State-wide Waste and Resource Recovery Infrastructure Plan* (Victoria 2017);
VIC	interstates (SA) or overseas	metals 32,985 t (25 %), paper & cardboard 2374 t (46 %), plastic 2074 t (74 %), TLR 445 t (45 %), glass 75 t (7 %), organics 656 t (1 %) of recovered C&D waste	Reprocessing (recycling)	Waste generation data source: *Victorian Recycling industry Annual Report 2015 - 16, Victorian Recycling industry Annual Report 2016 - 17*; *South Australia's Recycling Activity Survey 2017-18 Report*
NSW	VIC	68,000 tonnes of masonry waste	landfilling	
NSW	ACT	561,118 t of masonry waste	landfilling	Queanbeyan landfill waste went to the ACT; *National waste report 2018*- data base
ACT	NSW	masonry waste (unknown)	landfilling	ACT landfill waste sent to levy-free landfills in NSW; *National waste report 2018 pp84*
NSW	QLD	masonry waste 639, 747 t	landfilling	*National waste report 2018 pp84*; National waste report 2018 data base
QLD	interstates	masonry materials 243 t (< 0.1 %), metals 64,516 t (26 %), plastics 71 t (33 %), TLR 53 t (< 1 %) of recovered C&D waste	Reprocessing (recycling)	C&D waste generation data from the National Waste Report 2018 - database; Other data from the *Recycling and Waste in Queensland 2018*
SA	interstates	14,981 (48 %) metals, 1954 t (48 %) plastics	Reprocessing (recycling)	Generation data from national waste report 2018 data base; other data form *South Australia's Recycling Activity Survey 2017-18*
NT	SA	metals and glass (unknown amount)	Reprocessing (recycling)	*South Australia's Recycling Activity Survey 2017-18 Report*
NSW	SA	metals, plastics, glass, and other materials (unknown amount)	Reprocessing (recycling)	*South Australia's Recycling Activity Survey 2017-18 Report*
WA	SA	2237 t (2 %) metals. 11 t (< 1 %) paper & cardboard, and glass (unknown amount)	Reprocessing (recycling)	Generation data from national waste report 2018 data base; other data source: *Recycling Activity in Western Australia 2016-2017*
To overseas				
VIC	interstates (SA) or overseas	metals 32,985 t (25 %), paper & cardboard 2374 t (46 %), plastic 2074 t (74 %), TLR 445 t (45), glass 75 t (7 %), organics 656 t(1 %) of recovered C&D waste	Reprocessing (recycling)	Cross-border and export flows data extracted from *State-wide Waste and Resource Recovery Infrastructure Plan* (Victoria 2017); Waste generation data source: *Victorian Recycling industry Annual Report 2015 - 16, Victorian Recycling industry Annual Report 2016 - 17*; *South Australia's Recycling Activity Survey 2017-18 Report*
QLD	Overseas	237,725 t (75 %) metals waste, 1203 t (55 %) plastics	Reprocessing (recycling)	C&D waste generation data from the National Waste Report 2018 - database; Other data from the *Recycling and Waste in Queensland 2018*
SA	Overseas	15, 293 t (49 %) metals, 1, 995 t (49 %) plastics	Reprocessing (recycling)	Generation data from National Waste Report 2018 data base; other data form *South Australia's Recycling Activity Survey 2017-18*
WA	Overseas	2, 237 t (2 %) metals. 877 t (99 %) paper & cardboard materials	Reprocessing (recycling)	Generation data from National Waste Report 2018 data base; Other data source: *Recycling Activity in Western Australia 2016-2017*

Note: Normally, the recyclable materials after reprocessing will be further recycled.

Australia generated waste will be transported to overseas such as China, Malaysia, and Indonesia for further processing and recycling.

Based on the survey, it is found that QLD exported about 237,725 tons of metal waste (75 %) and 1203 tons of plastics (55 %) to overseas for reprocessing in 2017 along (Queensland Government, QG, 2018); SA exported about 15, 293 tons of metals (49 %) and 1, 995 tons of plastics (49 %) and WA exported about 2237 tons of metals (2 %), 877 tons of paper & cardboard materials (99 %) of recovered C&D waste overseas for reprocessing/recycling in the same year (Green Industries SA, GISA, 2019). Meanwhile, some of the Victoria's waste such as metals, paper & cardboard, plastic, TLR, and glass have been transported overseas but the data are combined with the waste to interstates (Sustainability Victoria, SV, 2018b).

5. Discussions

5.1. Drivers of C&D waste cross-regional mobility

5.1.1. Availability of facilities

In countries like Australia, which has a large land area but a small population (25.5 million in 2019 – Australian Bureau of Statistics), the scales of remote cities or towns are usually not significant. It is unrealistic for all cities or towns to have their C&D waste treatment and recycling facilities. The availability of facilities has become a critical reason for C&D waste cross-regional mobility. As discussed in the expert seminar, in some situations, there are no recycling facilities for certain waste materials in a particular region. Hence, waste processors have to find a destination with available treatment and recycling facilities. This leads to a common practice that some C&D waste materials such as metal, plastic, glass have been transported from rural areas to the metropolitan areas for further processing, which is particularly revealed in the *Victoria State-wide Waste and Resource Recovery Infrastructure Plan 2017* (Sustainability Victoria, SV, 2018a).

Due to geographical factors, in some border towns or cities, the closest waste management service such as recycling facilities or landfills are located on the other side of the border. The waste processors then prefer to send the waste to the adjacent regions for further processing or landfilling, considering the savings on transportation (Sustainability Victoria, SV, 2018a; Queensland Government, QG, 2019). Indeed, this type of cross-regional mobility can increase the rates of the waste been managed; since if there is no appropriate waste management facility nearby, the waste may be illegally dumped rather than recycled or appropriately landfilled.

5.1.2. Avoiding/reducing the landfill levy

As revealed in the expert seminar, avoiding/reducing the landfill levy is a critical reason for the cross-regional mobility of disposing of masonry waste outside of the originally generation region. This levy is in place to provide an incentive to divert materials from landfill and recover economic value. As presented in the results, the cross-border moving of C&D waste is not uncommon in the eastern regions of Australia, where the landfill levies are significantly different among regions. For instance, the landfill levy of C&D waste in the metro region of NSW can be posed to 140AUD/ton, yet there is no landfill levy of such waste in the neighbouring ACT. The Landfill levy for C&D waste has been applied in QLD from June 2019 for 75AUD/ton, which is still much lower than NSW. Landfill levy is the fee that is imposed by the government. Normally, the landfills will determine the landfill price according to the waste compositions (see Appendix Table A1). Noted by the "Government officer (C&D waste management related)" in the expert seminar, the differences of the landfill levy provide incentives to the transporters to select cheaper landfills across the border. Using cheaper landfill options interstate can give the practicians better economic benefits; however it can undermine governments' approach to waste management and resource recovery, as well as undermine the local market (Sustainability Victoria, SV, 2018a).

5.1.3. Market of the recycling industry

Since Australia is a market-based economy and the Australian Constitution also enshrines the freedom of trade between the states and territories, the industry can determine the C&D waste material streams flow to wherever the best economic benefits can be achieved (Department of the Environment and Energy, DoEE, 2018). *"Although the waste processer sometime will also transport the waste to their familiar downstream processer according to their traditional practice, they are most likely to send their waste materials to regions where there is a well-established recycling industry market"* (senior managers of two renowned C&D waste recycler in SA). As illustrated in the findings, although most of the C&D waste material streams generated in each state or territory remains in the state for reprocessing and management, there is a significant amount of C&D waste materials transported across state borders for recycling, and some materials are exported overseas.

5.2. The impacts of C&D waste cross-regional mobility

5.2.1. Environmental impacts

The cross-regional mobility of C&D waste will have multiple impacts on the waste management sector in states involved in waste cross-regional mobility. The moving of C&D waste from one region to another will directly affect the amount of waste being treated (Sustainability Victoria, SV, 2018a). All the waste treatment activities such as transportation, processing, recycling, energy recovery, landfilling, will need inputs of natural resources, consumption of energy, and generate certain outputs (Wang et al., 2019). Hence, the cross-regional mobility of C &D waste will affect the environmental performance of the waste processing and recycling system at regions involved in waste mobility activities.

As reported in Sustainability Victoria, SV (2018a), in some situations, the destinations of the waste disposal may not need to meet regulatory requirements in line with those in the regions where the waste were originally generated. In other words, the waste has been transported to other regions where they may not able to appropriately identify and handle the environmental risks brought from imported waste. As discussed in the expert seminar, one important purpose of some waste producers transporting their waste to other regions is to avoid regulatory requirement on the contents of the waste. Claimed by the "senior manager of renowned C&D waste recycler 1 in SA", they will refuse to take the waste bin if the contamination level is too high or they will charge an extremely high rate to manage the waste specifically. In this case, the waste producer may choose to find an alternative place that has less restrict regulation on the waste. This could increase potential community, environment and public health impacts at the destination, as the waste may not be treated appropriately and may contain harmful maters (Department of the Environment and Energy, DoEE, 2018).

5.2.2. Economic impacts

The cross-regional mobility will affect the supply and demand of waste management services and recycling products in the regions involving waste mobility (Sustainability Victoria, SV, 2018a). As discussed in the expert seminar, *"if a region has developed its advantage on waste recycling based on subsidy, the cross-regional mobility routes will be established for particular regions and the local recycling service industry of the disadvantaged regions may be destroyed. And once the subsidy has been declaimed, the whole recycling industry will be affected"*. Considering the industry scale in particular regions, the economic benefits of the involved communities will be significantly affected by waste cross-regional mobility (Sustainability Victoria, SV, 2018a).

Besides, if the recyclable waste materials have been concentrated in a particular region, the supply of recycled waste products will be increased dramatically. The increasing of recycled waste products will not only affect the established recycling market but also affect the natural raw materials market. As an example provided by the "senior manager of renowned C&D waste recycler 1 in SA", *"it is increasingly popular with the alternative fuel for energy recovery, an increasing amount of combustible waste materials have been made into the alternative fuel", "The business model is so successful and their company has developed the market in other countries in Southeast Asia", "The alternative fuel made by C&D waste will be a game-changer for the market"*. Hence, the waste cross-regional mobility can somehow impact the economic benefits on the whole supply chain.

5.2.3. Social impacts

As the waste cross-regional mobility will reduce the amount of waste being managed in the regions that transported their waste to other regions, the loss of these tonnages of C&D waste could present lost opportunities for the waste management service providers in the original regions where waste have been generated (Sustainability Victoria, SV, 2018a). When discussing the social impacts of the waste cross-regional mobility, the "senior manager of renowned C&D waste recycler 1 in SA" commented, *"It is a game that would satisfy the winner but will disappoint the disadvantaged player", "We have to cut down the production line for the timber chips as the opposite door can provide better products with a lower price", "They have expanded their business scale for several times during the last years and they have been recruiting new workers for a while"*. Thereby, the waste cross-regional mobility will affect employment in the local waste management service industry and bring significant social impacts on the communities involved in the waste management industry.

6. Conclusions

Investigating the generation, composition, and flows of C&D waste can provide fundamental data for further research and planning of waste management strategies and facilities. By conducting a series of site surveys, expert interviews, expert seminar and desktop surveys, this study gains an in-depth understanding of the treatment and management of C&D waste, particularly the waste cross-regional mobility phenomenon in Australia.

C&D waste management should be recommended as a critical sector of waste management in Australia, as C&D waste is the largest waste stream which contributes more than one-third of the total waste generation in Australia. An integrated waste management strategy could be developed to some types of C&D waste materials (such as metals, plastics, organics, paper & cardboard, glass), as the economic scale of waste treatment is a critical factor for evaluating the feasibility of recycling.

The recycling rate of the masonry materials is relatively high, as the masonry materials can be typically produced into recycled aggregate and rubber applied in road base/garden base. The recycling of masonry materials is very popular in the industry because of the well-established market and competitive price of recycled products. Some combustible materials such as organics, paper & cardboard, and TLR that can be made to alternative fuel are increasingly popular in the market, which expands the potential treatment methods of these waste materials.

There are three main forms of C&D waste cross-regional mobility in Australia: transport to interstates for recycling, transport to interstates for landfilling, and export to overseas for reprocessing/recycling. SA is identified as a centre of C&D waste cross-regional mobility for recycling in Australia. The state receives C&D waste materials for recycling from many other states (such as NT, NSW, WA, and VIC). The waste cross-regional mobility is quite dynamic in Australia's eastern regions such as NSW, ACT, VIC, and QLD. The findings show NSW is a major player in transporting its C&D waste particularly masonry waste to its neighbours, where these states or territories share the border and stand closely but the disposal fees are dramatically lower.

Although most masonry waste remains being processed or disposed of within the regions where it was generated, a considerable amount of such waste has been transported cross-border for landfilling and a minor portion of the waste has been sent to other regions for reprocessing/recycling. Waste materials such as metals, plastics, and paper & cardboard are more likely to be reprocessed in other regions or even overseas. The cross-regional mobility of C&D waste materials could be determined by several factors, including facilities availability, landfill levy, regulatory requirements, and market. The cross-regional mobility of C&D waste will have multiple impacts on the waste management sector in states involved in waste cross-regional mobility (including environmental, economic, and social performance), as the moving of C&D waste from one region to another will affect all aspects of waste treatment.

The findings enrich the body of knowledge of C&D waste management by expanding the traditional boundary from local-closed to cross-regional. With a better understanding of waste cross-regional mobility issues, countermeasures could be introduced to optimize C&D waste management performance at the system level.

CRediT authorship contribution statement

Huanyu Wu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Jian Zuo:** Supervision, Funding acquisition, Conceptualization, Methodology, Writing - review & editing, Validation. **Hongping Yuan:** Visualization, Methodology, Writing - review & editing. **George Zillante:** Supervision, Writing - review & editing. **Jiayuan Wang:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to acknowledge the financial support from the Adelaide Scholarship International, Australia (No. ASI-1712146) and Green Industries SA circular economy grant, Australia (No. 56121725/18GISA). The authors would like to thank the experts participated in the seminar and interviews. The authors would like to thank the organisations who hosted the site visits. The authors also would like to appreciate anonymous reviewers for their constructive comments that have been very useful to improve this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2020.104710.

Appendix

Table A1
Landfill levy in Australia (2018-19).

State	Waste type	Levy	Note
ACT	MSW	$96.05/t	No landfill fee for C&D waste applied
	C&I	$155.05/t	
	Mixed C&I with > 50 % recyclable material	$211.55/t	
NSW	Metro area:		Applied to C&D waste regarding the materials
	· Waste	$141.20/t	
	· Virgin excavated natural material	$127.08/t	
	· Shredder floc	$70.60/t	
	Regional area:		
	· Waste	$81.30/t	
	· Virgin excavated natural material	$73.17/t	
	· Shredder floc	$40.65/t	
	Coal washery rejects	$14.80/t	
NT	No landfill levy	N/A	N/A
QLD	Clean earth (Soil)	N/A	The waste levy for all classifications (including C&D waste) is proposed to increase by $5 on 1 July each year.
	C&D waste	$75/t	Last updated:21 June 2019
SA	Metro Adelaide:		Applied to C&D waste regarding the materials
	· Solid waste	$100/t	
	· Shredder floc	$62/t	
	Non-metro Adelaide:		
	· Solid waste	$50/t	
	· Shredder floc	$31/t	
	No levy for packaged asbestos waste		
VIC	Metro and regional:		
	· MSW	$64.30/t	
	· C&I and C&D	$64.30/t	Applied to C&D waste regarding the materials
	Rural:		
	· MSW	$32.22/t	
	· C&I and C&D	$56.36/t	Applied to C&D waste regarding the materials
WA	Putrescible	$70/t	
	Inert $105/m3	$70/t approx.	Applied to C&D waste regarding the materials

Note: C&D waste refers to construction and demolition waste; C&I waste refers to Commercial and industrial waste; MSW refers to Municipal Solid Waste.
Some governments impose the levy by waste type (such as MSW, C&I waste and C&D waste) and some governments determine the levy by the waste composition like inert waste.
Landfill levy is the fee that is imposed by the government. Normally, the landfills will determine the landfill price according to the waste compositions.
Source: National waste report 2018 (pp.40–41)

References

ACT Government, 2018. Waste Feasibility Study - Roadmap and Recommendations 2018. Available at:. https://s3.ap-southeast-2.amazonaws.com/hdp.au.prod.app.act-yoursay.files/2715/2566/4187/WFS_roadmap.pdf.

Ajayi, S.O., Oyedele, L.O., Akinade, O.O., Bilal, M., Owolabi, H.A., Alaka, H.A., Kadiri, K.O., 2016. Reducing waste to landfill: a need for cultural change in the UK construction industry. J. Build. Eng. 5, 185–193.

Alexeev, M., Chernyavskiy, A., 2018. A tale of two crises: federal transfers and regional economies in Russia in 2009 and 2014–2015. Econ. Syst. 42 (2), 175–185.

Bergsdal, H., Bohne, R.A., Brattebø, H., 2007a. Projection of construction and demolition waste in Norway. J. Ind. Ecol. 11 (3), 27–39.

Bergsdal, H., Brattebø, H., Bohne, R.A., Müller, D.B., 2007b. Dynamic material flow analysis for Norway's dwelling stock. Build. Res. Inf. 35 (5), 557–570.

Blengini, G.A., Garbarino, E., 2010. Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. Journal of Cleaner Production 18 (10-11), 1021–1030.

Chan, K.S., Dang, V.Q., Lai, J.T., Yan, I.K., 2011. Regional capital mobility in China: 1978-2006. J. Int. Money Finance 30 (7), 1506–1515.

Cochran, K., Townsend, T., Reinhart, D., Heck, H., 2007. Estimation of regional building-related C&D debris generation and composition: case study for Florida. US. Waste Management 27 (7), 921–931.

Coelho, A., de Brito, J., 2011. Generation of construction and demolition waste in Portugal. Waste Manag. Res. 29 (7), 739–750.

Department of the Environment and Energy, DoEE, 2018. Australia National Waste Report 2018. Available at:. . https://www.environment.gov.au/protection/waste-resource-recovery/national-waste-reports/national-waste-report-2018.

Dosho, Y., 2007. Development of a sustainable concrete waste recycling system. J. Adv. Concr. Technol. 5 (1), 27–42.

Esa, M.R., Halog, A., Rigamonti, L., 2017. Strategies for minimizing construction and demolition wastes in Malaysia. Resour. Conserv. Recycl. 120, 219–229.

European Commission, 2019. Construction and Demolition Waste, Waste Streams, Environment. Available at (2019). http://ec.europa.eu/environment/waste/construction_demolition.htm.

Green Industries SA, GISA, 2019. South Australia's Recycling Activity Survey 2017-18 Report. Available at:. . https://www.greenindustries.sa.gov.au/SArecycling.

Heininen, L., 2005. Impacts of globalization, and the circumpolar north in world politics. Polar Geogr. 29 (2), 91–102.

HKU, 2019. Towards Zero Waste Smart Cities in the Greater Bay Area – Establishing a Waste Trade Organisation (WTO) for Construction Waste Materials. Available at:. https://www.hku.hk/press/news_detail_19281.html.

Hu, M., Van Der Voet, E., Huppes, G., 2010. Dynamic material flow analysis for strategic construction and demolition waste management in Beijing. Journal of Industrial Ecology 14 (3), 440–456.

Lau, H.H., Whyte, A., Law, P.L., 2008. Composition and characteristics of construction waste generated by residential housing project. Int. J. Environ. Res. 2 (3), 261–268.

Li, J., Zuo, J., Cai, H., Zillante, G., 2018a. Construction waste reduction behavior of contractor employees: an extended theory of planned behavior model approach. J. Clean. Prod. 172, 1399–1408.

Li, J., Zuo, J., Guo, H., He, G., Liu, H., 2018b. Willingness to pay for higher construction waste landfill charge: a comparative study in Shenzhen and Qingdao. China. Waste Management 81, 226–233.

Li, S., Wu, H., Ding, Z., 2018c. Identifying sustainable wood sources for the construction industry: a case study. Sustainability 10 (1), 139.

Liu, J., Nie, J.J., Yuan, H.P., 2019. To expand or not to expand: a strategic analysis of the recycler's waste treatment capacity. Comput. Ind. Eng. 130, 731–744.

Lu, W., Yuan, H., 2010. Exploring critical success factors for waste management in construction projects of China. Resour. Conserv. Recycl. 55 (2), 201–208.

Lu, W., Chen, X., Ho, D.C., Wang, H., 2016. Analysis of the construction waste management performance in Hong Kong: the public and private sectors compared using big data. J. Clean. Prod. 112, 521–531.

Lu, W., Chen, X., Peng, Y., Shen, L., 2015. Benchmarking construction waste management performance using big data. Resour. Conserv. Recycl. 105, 49–58.

Mália, M., de Brito, J., Pinheiro, M.D., Bravo, M., 2013. Construction and demolition waste indicators. Waste Management & Research 31 (3), 241–255.
Miatto, A., Schandl, H., Forlin, L., Ronzani, F., Borin, P., Giordano, A., Tanikawa, H., 2019. A spatial analysis of material stock accumulation and demolition waste potential of buildings: a case study of Padua. Resour. Conserv. Recycl. 142, 245–256.
Miguélez, E., Moreno, R., 2015. Knowledge flows and the absorptive capacity of regions. Res. Policy 44 (4), 833–848.
NSW EPA, 2019a. Waste and Resource Recovery Infrastructure Needs Report 2017-21. Available at:. . https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/wastestrategy/epa-waste-and-resource-recovery-infrastructure-strategy-epa2017p0169.pdf?la = en&hash = 58087743D18F89DD199C4CD62EF2373A46436F7C.
NSW EPA, 2019b. Waste Avoidance and Resource Recovery Strategy Progress Report. Available at:. pp. 2017–2018. https://www.epa.nsw.gov.au/publications/wastestrategy/19p1690-warr-strategy-progress-report-2017-18.
Queensland Government, QG, 2018. Recycling and Waste in Queensland 2018 Report. Available at:. . https://www.qld.gov.au/environment/pollution/management/waste/recovery/data-reports/recycling-waste.
Queensland Government, Q.G., 2019. Transforming Queensland's Recycling and Waste Industry Directions Paper. Available at:. https://www.qld.gov.au/_data/assets/pdf_file/0021/69060/transforming-qlds-recycling-waste-industry-directions-paper.pdf.
Saarivirta, T., Consoli, D., 2014. Where did they go? A study on newly established universities and graduate mobility in Finland. The Economics of Knowledge Generation and Distribution. Routledge, pp. 92–116.
Shen, L.Y., Tam, V.W., Tam, C.M., Drew, D., 2004. Mapping approach for examining waste management on construction sites. J. Constr. Eng. Manag. 130 (4), 472–481.
Singh, J., 2008. Distributed R&D, cross-regional knowledge integration and quality of innovative output. Res. Policy 37 (1), 77–96.
Solís-Guzmán, J., Marrero, M., Montes-Delgado, M.V., Ramírez-de-Arellano, A., 2009. A Spanish model for quantification and management of construction waste. Waste Manag. 29 (9), 2542–2548.
Song, J., Almeida, P., Wu, G., 2003. Learning–by–hiring: when is mobility more likely to facilitate interfirm knowledge transfer? Manage. Sci. 49 (4), 351–365.
Stephan, A., Athanassiadis, A., 2018. Towards a more circular construction sector: estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. Resour. Conserv. Recycl. 129, 248–262.
Sustainability Victoria, SV, 2017. Victorian Recycling Industry Annual Report. 2015–2016. Available at:. . https://www.sustainability.vic.gov.au/About-us/Publications/Waste-VRIAR-2015-2016.
Sustainability Victoria, SV, 2018a. State-wide Waste and Resource Recovery Infrastructure Plan (Victoria 2017). Available at:. https://www.sustainability.vic.gov.au/about-us/what-we-do/strategy-and-planning/statewide-waste-and-resource-recovery-infrastructure-plan.
Sustainability Victoria, SV, 2018b. Victorian Recycling Industry Annual Report. 2016–2017. Available at:. . https://www.sustainability.vic.gov.au/About-us/Publications/Waste-VRIAR-2016-2017.
Tanikawa, H., Hashimoto, S., 2009. Urban stock over time: spatial material stock analysis using 4d-GIS. Build. Res. Inf. 37 (5-6), 483–502.
Udawatta, N., Zuo, J., Chiveralls, K., Zillante, G., 2015. Improving waste management in construction projects: an Australian study. Resour. Conserv. Recycl. 101, 73–83.
Wang, J., Wu, H., Tam, V.W., Zuo, J., 2019. Considering life-cycle environmental impacts and society's willingness for optimizing construction and demolition waste management fee: an empirical study of China. J. Clean. Prod. 206, 1004–1014.
Waste Authority WA, 2018. Recycling Activity in Western Australia. 2016 – 2017. Available at:. https://www.wasteauthority.wa.gov.au/media/files/documents/Recycling_Activity_in_Western_Australia_2016-17.pdf.
Wiedenhofer, D., Steinberger, J.K., Eisenmenger, N., Haas, W., 2015. Maintenance and expansion: modeling material stocks and flows for residential buildings and transportation networks in the EU25. J. Ind. Ecol. 19 (4), 538–551.
Wu, H., Duan, H., Zheng, L., Wang, J., Niu, Y., Zhang, G., 2016a. Demolition waste generation and recycling potentials in a rapidly developing flagship megacity of South China: prospective scenarios and implications. Constr. Build. Mater. 113, 1007–1016.
Wu, H., Wang, J., Duan, H., Ouyang, L., Huang, W., Zuo, J., 2016b. An innovative approach to managing demolition waste via GIS (geographic information system): a case study in Shenzhen city. China. Journal of Cleaner Production 112, 494–503.
Wu, H., Yuan, H., Wang, J., Ouyang, L., Li, Z., 2017. An investigation of demolition waste management: case of Shenzhen in China. Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate. Springer, Singapore, pp. 1157–1167.
Wu, H., Zuo, J., Yuan, H., Zillante, G., Wang, J., 2019a. A review of performance assessment methods for construction and demolition waste management. Resour. Conserv. Recycl. 150, 104407.
Wu, H., Zuo, J., Zillante, G., Wang, J., Yuan, H., 2019b. Status quo and future directions of construction and demolition waste research: a critical review. J. Clean. Prod., 118163.
Wu, Z., Ann, T.W., Shen, L., Liu, G., 2014. Quantifying construction and demolition waste: an analytical review. Waste Manag. 34 (9), 1683–1692.
Yeheyis, M., Hewage, K., Alam, M.S., Eskicioglu, C., Sadiq, R., 2013. An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability. Clean Technol. Environ. Policy 15 (1), 81–91.
Yuan, H., Wang, J., 2014. A system dynamics model for determining the waste disposal charging fee in construction. Eur. J. Oper. Res. 237 (3), 988–996.
Yuan, H.P., Yang, Y., 2020. BIM adoption under government subsidy: technology diffusion perspective. J. Constr. Eng. Manag. 146 (1). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001733.
Zheng, L., Wu, H., Zhang, H., Duan, H., Wang, J., Jiang, W., Dong, B., Liu, G., Zuo, J., Song, Q., 2017. Characterizing the generation and flows of construction and demolition waste in China. Constr. Build. Mater. 136, 405–413.

Appendix D: Published paper in *Journal of Cleaner Production*

Statement of Authorship

Title of Paper	Status quo and future directions of construction and demolition waste research: A critical review
Publication Status	☒ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Wu, H., Zuo, J., Zillante, G., Wang, J., & Yuan, H. (2019). Status quo and future directions of construction and demolition waste research: A critical review. *Journal of Cleaner Production*, 240, 118163. https://doi.org/10.1016/j.jclepro.2019.118163.

Principal Author

Name of Principal Author (Candidate)	Huanyu Wu		
Contribution to the Paper	Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft		
Overall percentage (%)	60%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	05/05/2020

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Jian Zuo		
Contribution to the Paper	Supervision, Conceptualisation, Methodology, Writing - review & editing, Validation		
Signature		Date	7/5/2020

Name of Co-Author	George Zillante		
Contribution to the Paper	Supervision, Writing - review & editing		
Signature		Date	7/5/2020

Name of Co-Author	Jiayuan Wang		
Contribution to the Paper	Supervision, Writing – review & editing.		
Signature		Date	07/05/2020

Name of Co-Author	Hongping Yuan		
Contribution to the Paper	Visualisation, Methodology, Writing - review & editing		
Signature		Date	07/05/2020

Journal of Cleaner Production 240 (2019) 118163

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Status quo and future directions of construction and demolition waste research: A critical review

Huanyu Wu [a], Jian Zuo [a, b], George Zillante [a], Jiayuan Wang [b], Hongping Yuan [c, *]

[a] *School of Architecture and Built Environment, The University of Adelaide, SA, 5001, Australia*
[b] *School of Civil Engineering, Shenzhen University, Shenzhen, 518060, PR China*
[c] *School of Management, Guangzhou University, Guangdong, 510006, PR China*

A R T I C L E I N F O

Article history:
Received 10 October 2018
Received in revised form
10 August 2019
Accepted 24 August 2019
Available online 26 August 2019

Handling editor: Yutao Wang

Keywords:
Construction and demolition waste
Waste management
Waste reduction
Waste recycling
Review

A B S T R A C T

Due to significant environmental, social, and economic impacts, the last decades have witnessed a rapid growth of research related to construction and demolition (C&D) waste. By employing a systematic literature review approach, this study examined C&D waste related articles published since the 1990s in order to explore future research directions. Results show the current C&D waste research has been carried out from various perspectives. These mainly include environmental science and environmental engineering, material science and engineering, industrial ecology, management science, and architecture, engineering, construction and operation of buildings. Consequently, several future research opportunities are identified. These future research opportunities are: (1) identifying pollutants in C&D waste derived from industrial buildings; (2) developing comprehensive pollutant control measures to treat C&D waste; (3) improving the recyclability of C&D waste; (4) developing the advanced performance evaluation criteria for wasted materials and recycled products; (5) extending the research boundary of C&D waste flows; (6) understanding the dynamics and mobility during the life cycle of C&D waste; (7) developing C&D waste disposal charging system; (8) developing advanced methods to assess the C&D waste management performance; (9) exploring the more efficient use of information technologies in C&D waste management; (10) reducing C&D waste from early project stages; and (11) reducing C&D waste during the building operation. These findings are not only valuable to better understand the C&D waste research, but also useful to assist practitioners to further improve C&D waste management performance, and mitigate associated pollution.

1. Introduction

A large quantity of construction and demolition (C&D) waste is generated every year, much of which has the potential to be recycled (EC, 2016). For example, over 10 billion tons of C&D waste are generated worldwide every year, among which the United States contributes about 700 million tons (Jain et al., 2015); the European Union contributes over 800 million tons (Ajayi et al., 2016); and China contributes around 2300 million tons (Zheng et al., 2017). Compositions of C&D waste may vary from one region to the other due to the different economy, natural environment, and construction practices. However, the mass of bulky wastes such as concrete and bricks usually account for 70–80% of the total waste (Bernardo et al., 2016). In particular, inert C&D waste (e.g., concrete and bricks) can be recycled into aggregate, which can be used mainly in road pavement or as the input of recycled materials (e.g., mortar, concrete, and bricks) (Garcia-Gonzalez et al., 2014; Vegas et al., 2015). Meanwhile, a small fraction of C&D waste contains hazardous components (e.g., asbestos) that have severe impacts on human health, the natural environment, and the society (Roussat et al., 2008). Therefore, there is a pressing need to manage C&D waste and associated impacts.

To respond to such a challenge, significant endeavours have been undertaken to study various aspects of C&D waste, such as examining waste management practices in major economies like Canada (Yeheyis et al., 2013), Germany (Karavezyris, 2007), United States (Warren et al., 2007), United Kingdom (Soutsos and Fulton, 2016), China (Lu and Yuan, 2010), Australia (Udawatta et al., 2015a), and Malaysia (Esa et al., 2017). Some studies have attempted to investigate material flows and networks from waste

* Corresponding author.
E-mail address: hpyuan2005@gmail.com (H. Yuan).

https://doi.org/10.1016/j.jclepro.2019.118163
0959-6526/

generation to final disposal (Bergsdal et al., 2007a,b; Kucukvar et al., 2014). Furthermore, the performance of C&D waste management has been evaluated from the perspective of sustainability, feasibility, viability (Jung et al., 2015), and waste management efficiency (Ajayi et al., 2015; Tam, 2008). As that solutions to waste minimisation can be related to the waste recycling techniques (Park and Tucker, 2017), the physical and ecological impacts of C&D waste have been investigated by assessing and handling heavy metals and organic compositions that are leached out from the waste (Denyes et al., 2014), as well as by testing and improving the physical performances such as the strength and durability of recycled products (Evangelista and de Brito, 2017; Tam and Tam, 2009).

Some review articles on C&D waste have been published. These reviews can be broadly classified into two categories. The first category of reviews took the general perspective of C&D waste management. For example, Meyer (2009) summarised the development of the substitution of various recycled materials for aggregates. Lu and Yuan (2011) identified three major topics in C&D waste management based on a critical review of 147 articles from 1996 to 2010. Yuan and Shen (2011) further analysed the research trend on C&D waste management by 2010. The second category focused on a specific aspect of C&D waste management and recycling. In terms of quantifying C&D waste, some studies reviewed the methods that are capable of quantifying the waste generation (Abanda et al., 2013; Wu et al., 2014). Based on 236 articles published from 1977 to 2014, Silva et al. (2014) identified critical factors to the physicochemical properties of recycled aggregates in a bid to improve the efficiency of concrete production. Later, Silva et al. (2015a) reviewed existing models to predict the physical property of recycled aggregate concrete, which was further enhanced by (Lye et al., 2016). Tam et al. (2018) reviewed the recycled aggregate in concrete applications in the last two decades. These reviews provide valuable insights into C&D waste management and recycling by either exhibiting a big picture of the discipline or looking into some specific topics that are worth further investigation. It is unclear, however, how C&D waste research has evolved over the period. In particular, it remains unclear whether the C&D waste management discipline has been reshaped compared with the findings provided by previous reviews, such as (Lu and Yuan, 2011) and (Yuan and Shen, 2011). It is also worth noting that existing reviews have been taken either from management or technical perspective. There is generally a lack of critical review on C&D waste literature via a holistic approach covering both aspects.

Therefore, this study aims to better understand the current status of C&D waste research and to identify future research opportunities through a comprehensive review of C&D waste research from 1994 to 2018. This study extends prior studies by: (1) a more comprehensive coverage in both time spanned topics of sample articles. In particular, this study will not limit itself on waste management only. Instead, it will cover articles in multiple disciplines, including environmental science and environmental engineering, material science and engineering, industrial ecology, and management science; and (2) an in-depth content analysis to reveal the evolution and future directions of C&D waste research.

The remainder of the paper is organized as follows. Section 2 presents an introduction to the methodology for selecting samples and conducting the critical review. Current status and future directions of C&D waste research are discussed in section 3 and section 4, respectively. Finally, we conclude the paper by summarising the key findings.

2. Methodology

2.1. Adoption of the systematic literature review

For any research field, it is essential to review existing literature. A useful literature review creates a solid foundation to advance knowledge in a specific field by facilitating theory development and identifying the research status as well as possible directions. Hence, the literature review has been a critical feature of accelerating discipline development (Webster and Watson, 2002).

There are some common structures for executing a review (Webster and Watson, 2002). These include: (a) providing a working definition of key variables and setting the boundaries on the work; (b) identifying the relevant literature via appropriate data sources; (c) analysing the literature via a concept centric approach; and (d) structuring the review based on the sensemaking idea and writing the review via appropriate tone (not over critical) and effective tense (present or past tense).

Compared with other methods (e.g., expert review), a systematic literature review methodology has both strengths and weaknesses (Grant and Booth, 2009). Firstly, a literature review would not be affected by the location of conducting the research. The researcher can conduct a review in the office, library, or even at home. Secondly, the expert review may require substantial research resources, including academic and industry networks. However, it is more accessible to the data for a literature review. Thirdly, when conducting a literature review, the researchers can refine the search and analysis repeatedly, but it is unlikely to repeat the expert review overtime (Randolph, 2009).

However, there are some weaknesses in systematic reviews. First, it is time-consuming, which may take several months from the initial reading to complete writing (Zopounidis and Doumpos, 2002). A useful literature review should be in-depth in a particular research field to extract crucial information. Due to the overwhelming number of published articles and resources required (e.g., time spent on reading, analysis, and writing), the review may not always catch up with the most updated knowledge of the field. Second, a literature review can hardly capture all published articles due to the limitation of database access (Boote and Beile, 2005). There are always some fruitful articles hiding in some less popular journals, which may not be included in one well-known database such as Web of Science or Scopus. This study develops two strategies to overcome these problems, which will be discussed subsequently.

2.2. Research procedure

To fulfil the research aim, the study adopts the following procedure. This procedure consists of initial sample selection, article reading and analysing, review structuring, sample updating, and adding.

2.2.1. Initial sample selection

Currently, several databases are available such as PubMed, Scopus, Web of Science (WoS), and Google Scholar for indexing research articles. Falagas et al. (2008) suggested that WoS has the highest coverage in natural science and engineering field and good coverage in terms of social science, arts and humanities (Mongeon and Paul-Hus, 2016). Therefore, WoS is considered as critical to extract articles both in waste management and waste recycling techniques. Meanwhile, through re-visiting the journal list identified by previous review articles on C&D waste, it is found that most of these journals have been included in the WoS database.

Therefore, WoS is determined as the primary source for searching and filtering articles. Scopus and Google Scholar are used for updating and adding article samples.

We used the *Advanced Search function* provided by the WoS core collection database for the initial sampling. The search was carried out on 1st March 2018 with the following model: (*TS* = (*"construction waste" OR "demolition waste" OR "construction and demolition waste" OR "C&D waste"*)) *AND LANGUAGE: (English) AND DOCUMENT TYPES:* (*Article*)*; Indexes* = *SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, IC Timespan* = *All years.* Initially, a total of 1027 articles were retrieved from the Web of Science database. All these papers were published since the 1990s.

2.2.2. Article reading and analysing

Articles identified from the initial sample selection were downloaded from the database. Consequently, these articles were scanned and analysed following two stages. During the March and April in 2018, the initially selected items were quickly viewed through the title and abstract. The purposes of this step are to extract fruitful articles and to classify the items into different themes and concepts. In the next step (May to July 2018), the retrieved articles were critically reviewed, and the themes and concepts were structured according to the research focus. Finally, 156 related articles were critically reviewed, and five themes including ten concepts were identified.

2.2.3. Review structuring

Initially, we outlined several broad research themes to cover the full range of C&D waste research interests, e.g., environmental, technical, materials, management, and industrial ecology. By analysing the contents of selected articles, we determined the concepts of these studies and fitted them into the identified themes. During this process, we extended and combined the themes to suit the concepts that were identified based on the critical review.

Based on the critical review of selected articles, a conceptual model for the mainstreams of C&D waste research was developed. By examining the research question, research methods, and main findings, critical knowledge gaps in the current research were identified (details provided in Section 3). Meanwhile, by extending current theories and concepts in prior studies, potential research opportunities were proposed for future research (details presented in Section 4). Based on these works, the review was structured and completed during August and September 2018.

2.2.4. Sample updating and adding

Significant amount of time is required for reading and analysing articles, review structuring, and writing. Therefore, it is necessary to update the sample timely. Google Scholar was chosen to track the latest publications in C&D waste. To avoid missing essential themes and concepts, the research team frequently discussed the contents of the review paper with their colleagues. It is noticed that the perspective of AECO (Architecture, Engineering, Construction and Operation of buildings) and the concept of concrete recycling were added to the theoretical model during the process.

3. Mainstreams of C&D waste research: current status

According to their research focus, the sampled articles can be classified into five mainstreams (see Fig. 1). These five mainstreams are: (1) environmental concerns of C&D waste – from environmental science and environmental engineering perspectives; (2) C&D waste recycling – from material science and engineering perspective; (3) addressing the sustainability of C&D waste – from an industrial ecology perspective; (4) improving C&D waste management – from management science perspective; and (5) reducing the C&D waste – from architecture, engineering, construction and operation of buildings perspective. In the following section, these mainstreams will be discussed in detail to formulate a holistic review of the existing body of knowledge on C&D waste.

3.1. Environmental concerns of C&D waste – from environmental science and environmental engineering perspectives

The most common environmental concerns of C&D waste are the pollution of overland water (Ferguson and Male, 1980), groundwater (Lee et al., 2008), and soils (Kalbe et al., 2008; Cabalar et al., 2016). These have received extensive attention from scholars with environmental science and environmental engineering backgrounds. These studies attempt to examine the environmental impacts of C&D waste through testing the pollutant compositions of the waste and analysing the influence of pollutants in C&D waste on the total environment.

3.1.1. Identification of pollutant composition from C&D waste

Identification of pollutant compositions from C&D waste plays an essential role in understanding the environmental concerns of C&D waste. Pollutant compositions of C&D waste may vary, such as heavy metals (e.g., copper and chromium), organic matter (e.g., polycyclic aromatic hydrocrack (PAH), carbon, methane, sulfuret and hydrogen sulphide) (Jang and Townsend, 2001; Van Praagh and Modin, 2016). Notably, efforts have been made to identify and quantify heavy metals released from C&D waste and associated impacts on the surrounding environment (Oygard et al., 2005). Some studies assessed the effective rates of heavy metals released from the waste (Wehrer and Totsche, 2008), while others concentrated on the heavy metal migration measures (Shin and Kang, 2015). Overall, the research work in this area is relatively robust, as many results are based on experimental studies in the laboratories of leading universities and institutes. However, since the sample selection was limited to residential/commercial project sites and landfills, some toxicity pollutants have been overlooked. Recently, some toxicity organic matter components such as polycyclic aromatic hydrocrack and hydrogen sulphide have been found in mixed C&D waste derived from the demolition of industrial buildings such as pesticide factory (Duan et al., 2016). The composition and properties of mixed C&D waste are very complex. As a result, the environmental and health risks associated with industrial C&D wastes have drawn wide concerns (Huang et al., 2016, 2017).

3.1.2. Control and mitigation of pollution from C&D waste

To control and mitigate the pollution from C&D waste, studies have been conducted on the mechanism of sorption, adsorption, release, immobilization, incineration, and pyrolysis (Delay et al., 2007; Iden et al., 2008; Shin et al., 2016). Based on the long-term monitoring, Johnson et al. (1999) revealed that C&D waste landfill would produce liquids such as leachate containing multiple biomasses, and generate landfill gas. Bergersen and Haarstad (2014) found that the mixed demolition waste containing gypsum-based plasterboard in the landfill would generate hydrogen sulphide (H_2S) gas, which is typical for landfill gas and major odorant landfills. The removal of nitrogen and organic substances from the landfills has become a critical issue. Hence, it is imperative to introduce technical measures to minimise the release of pollutants from C&D waste disposal sites.

3.1.3. Methods to evaluate environmental impacts of C&D waste

The occurrence of keywords showed that "leaching test" has been frequently adopted to test the pollutants and related environmental impacts (Engelsen et al., 2017; Van Praagh and Modin,

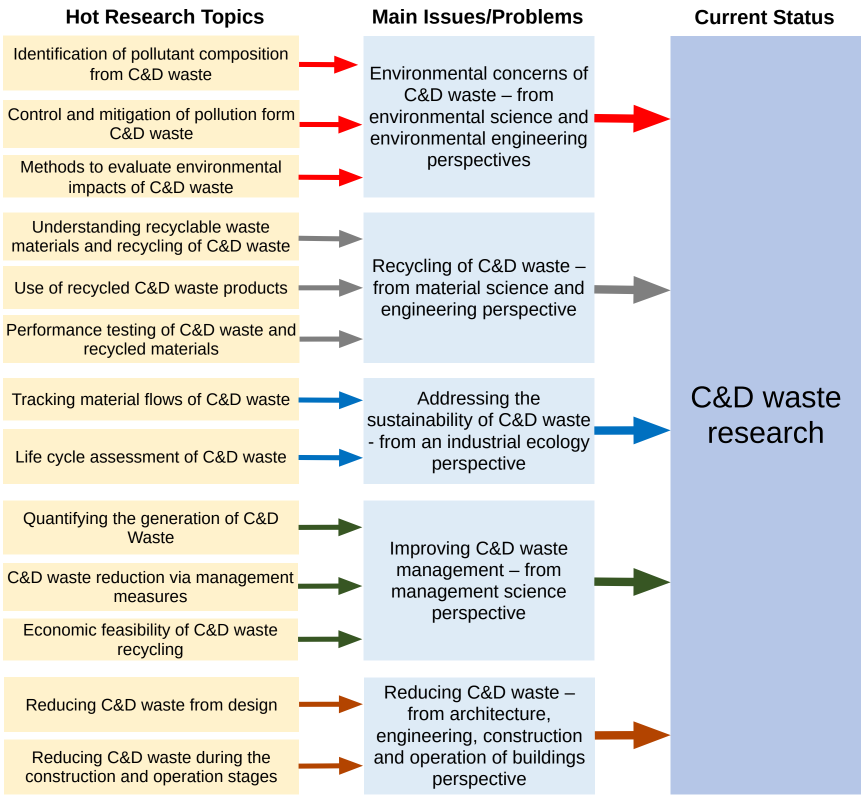


Fig. 1. Mainstreams of C&D waste research.

2016). Leaching tests have been examined extensively over the last two decades, and the leaching laboratory environment could closely approximate the waste disposal site where C&D waste would contact liquid from rainfall. Galvin et al. (2012) compared the leaching tests in batches while their study focused on how pH value may affect the mechanism of metal releasing from C&D wastes. Similarly, Kruger et al. (2012) conducted experiments on how heavy metals and PAH may be released from the waste through leaching. However, the leaching behaviour can change dramatically and it is sensitive to the different environment. Therefore, a single test method may not be able to meet the accuracy requirement for evaluating environmental impacts of C&D waste. This is due to the potential risk that such pollutants within the hazardous C&D waste could release when mixing with other waste materials in landfills (Roussat et al., 2008).

3.2. Recycling of C&D waste — from material science and engineering perspectives

C&D waste recycling is another active research area, most of which was conducted from the perspective of material science and engineering. The detailed topics mainly include understanding recyclable waste materials and recycling of C&D waste, the use of recycled C&D waste products, and performance testing of recycled products from C&D waste. Table 1 shows the recyclable C&D waste materials, recycled products and the use of recycled products identified from previous studies.

3.2.1. Understanding recyclable waste materials and recycling of C&D waste

C&D waste materials such as concrete, mortar, brick, and glass have attracted the most attention, where concrete and brick are usually crushed to make recycled aggregate (Garcia-Gonzalez et al., 2014; Vegas et al., 2015; Kumar, 2017; Hou et al., 2016). Mortars are usually crushed to make recycled sand (Ulsen et al., 2013; Stefanidou et al., 2014). Meanwhile, cement mortar adhered on the surface of aggregate is viewed as undesirables and thus needs to be removed from recycled aggregate (Tam et al., 2007). As another critical C&D waste material, glass has been considered to have great potential to be recycled (Kralj, 2009; Penacho et al., 2014; Arulrajah et al., 2014). Considering the number of studies on C&D waste recycling, the study of recycled aggregate and recycling concrete dominated the theme as masonry waste accounts for almost 90% of C&D waste generation in terms of weight. Compared to other waste materials (e.g. glass, timber, and plastics), this kind of waste is technically more accessible to be recycled and economically

Table 1
C&D waste materials, recycled products and use of recycled products.

C&D waste materials	Recycled products	Use of recycled products	Typical studies
Concrete	Recycled aggregate	Pavement Base/Subbase	(Garcia-Gonzalez et al., 2014; Vegas et al., 2015; Gomes et al., 2015)
		Hot mix asphalt (the hot mix asphalt is normally made with recycled concrete aggregates coated with bitumen emulsion)	(Rafi et al., 2014; Gomez-Meijide et al., 2016; Pasandin and Perez, 2013, 2014)
Mortar	Recycled sand	Mortars	(Ulsen et al., 2013; Miranda et al., 2013, 2014)
Brick	Crushed brick aggregates	Pavement base/Subbase	Hou et al. (2016)
Glass	Recycled glass blends	Pavement Base/Subbase (adding glass blends into mortar and concrete to improve the physico-mechanical performance)	(Arulrajah et al., 2014; Kralj, 2009; Penacho et al., 2014)
_	Mixed composite powder materials	Cementitious materials in small-scale prefabricated concrete	Xue et al. (2016)
_	Mixed recycled components (e.g. recycled mixed fine aggregate)	Fillers	(Belagraa et al., 2017; Choudhary et al., 2016)

feasible due to the scale effect. As a result, the treatment of remain waste fractions has been overlooked. This may cause severe impacts on human health and the natural environment because some unclassified materials contain hazardous components (e.g., asbestos) (Gualtieri, 2013).

3.2.2. Use of recycled C&D waste products

Recycled C&D waste products (e.g., recycled aggregate, recycled sand, crushed brick aggregate, and recycled glass blends) can be used in different contexts. For instance, recycled aggregate is frequently used in concrete, large volumes in pavement base or subbase (Arulrajah et al., 2013; Xuan et al., 2016; Leite et al., 2011; Kumar, 2017) and while sound quality recycled aggregate also used to produce pre-cast and structural concrete (Tam et al., 2018). The recycled concrete aggregate could be used to produce the hot mix asphalt while bitumen emulsion is used for coating purpose (Pasandin and Perez, 2013, 2014; Gomez-Meijide et al., 2016). As a recycled product screened from the crushing of mortars, recycled sand can be used as mortar component (Ulsen et al., 2013; Miranda et al., 2013, 2014; Stefanidou et al., 2014).

Besides, crushed brick aggregates and recycled glass blends can be used as additional materials in some applications. For instance, it can be used to make the base of the asphalt pavement (Hou et al., 2016). Similarly, recycled glass blends can be added into mortar and concrete to improve their physical-mechanical performance (Kralj, 2009; Penacho et al., 2014). This can be applied in pavement base/subbase as well (Arulrajah et al., 2014). In addition, Xue et al. (2016) introduced the utilization of C&D waste composite powder materials (e.g., recycled sand blends) in prefabricated concrete.

Although various applications of recycled C&D waste products have been developed, they are mainly based on the recycled aggregate related products due to the technique and economic feasibility. Other materials can also be used in some applications. For instance, mixed recycled components have been used as filler (Choudhary et al., 2016; Belagraa et al., 2017). Timber can be used in land re-habitations, soil improvement, and urban development. These applications have been used in practice for years but have not been documented in prior studies, which might limit the growth of recycled C&D waste applications.

3.2.3. Performance testing of C&D waste and recycled materials

Several studies have been undertaken to test the performance of C&D waste and recycled materials (mainly recycled aggregates). The performance evaluation has been taken from various perspectives such as efficiency of utilization (Anastasiou et al., 2014; Ho et al., 2013), physical and mechanical properties/performance (Belagraa et al., 2017; da Silva et al., 2014; Matias et al., 2013; Zega et al., 2010), and mechanical behaviours (Corinaldesi and Moriconi, 2009; Gao et al., 2017; Tam et al., 2015a). In addition, other aspects such as macroscopic and microstructural properties of recycled concrete have also been examined (Li and Yang, 2017).

Meanwhile, some studies focused on specific performance testing (e.g., deformation, tensile strength, compressive strength, resistance, durability, stiffness, etc.) of recycled aggregate in concrete. For instance, Tam, et al. (2015) investigated the deformation behaviour of recycled aggregate from a long-term perspective whereas Silva et al. (2015b) focused on the tensile strength behaviour. Sim and Park (2011) examined compressive strength and durability resistance for recycled aggregate concrete. Both fly-ash and fine recycled aggregate were considered useful when mixed to the concrete. Other studies investigated the durability of multiple recycled products, including: concrete consisting recycled aggregates (Lovato et al., 2012; Bravo et al., 2015), fine recycled aggregates (Vieira et al., 2016), cold asphalt emulsion mixtures (Nassar et al., 2016), recycled ceramic aggregates (Correia et al., 2006), blended cements (Bjegovic et al., 2012) and recycled lime powder (Kanellopoulos et al., 2014). In addition, stiffness is a common performance indicator (Gomez-Meijide et al., 2015).

The studies on the performance testing of C&D waste and recycled materials usually form part of research projects aiming at recycling C&D waste. This kind of studies can be viewed as additional research support for the original research on recycling C&D waste. Since studies on materials and structures have been conducted for decades, the research methods used in such studies are very traditional and reliable. However, new approaches are very rare.

3.3. Addressing the sustainability of C&D waste - from an industrial ecology perspective

A considerable amount of C&D waste studies has been undertaken from the perspective of industrial ecology. As an interdisciplinary approach, industrial ecology concerns various issues in the industrial system such as material flows, life cycle impacts, and dynamics of industry technology (Erkman, 1997).

3.3.1. Tracking material flows of C&D waste

In the context of industrial ecology, the dynamics of C&D waste is highlighted. To better understand this issue, many efforts have been devoted to tracking the waste material flows (i.e., from waste generation to final disposal). For instance, Huang and Hsu (2003) incorporated resource and material flow analysis to investigate the urban sustainability issues in Taipei. Blengini and Garbarino (2010) analysed the energy and environmental implications of the C&D waste recycling chain in Italy. Wiedenhofer et al. (2015) examined the non-metallic minerals in the EU25 in terms of stocks and flows.

Similarly, understanding the trends and dynamics of C&D waste processing is another focus. For instance, Hu et al. (2010) analysed the urban housing system in Beijing, following a dynamic material flow approach. Hiete et al. (2011) argued that the C&D waste recycling network should be considered as an integral part of supply and demand chain at the regional level where its dynamics should be taken into account during the planning process. Although many studies have attempted to address this issue, the dynamic material flows of C&D waste remains unclear. There is a lack of effective approaches apart from the widely-adopted bottom-up waste management data report practice to collect waste flow data. It can hardly provide accurate waste flow data as the authority only documents the waste generated within their jurisdiction whereas have few accurate data about the waste transported out to other regions. Meanwhile, the cross-regional transport of C&D waste makes the material flows more dynamic, which would further affect the accuracy of tracking C&D waste flows.

3.3.2. Life cycle assessment of C&D waste

The primary purpose of studying the life cycle assessment of C&D waste is to promote the sustainability of construction industry. This is because the generation of C&D waste takes place during two crucial life cycle stages (i.e., construction and demolition) and other stages (e.g., design and operation) of buildings and infrastructure (Blengini, 2009), and the management of waste would affect the whole life cycle performance of the project. Thus, life cycle assessment approach is applied in C&D waste studies (Kucukvar et al., 2016; Mercante et al., 2012; Wu et al., 2015), whose main focuses include:

- *Developing models to assess the life cycle impacts of processing C&D waste.* Several studies developed impact assessment methods and indicators to assess the impacts of C&D waste treatment (i.e., environmental impacts, economic impacts, and social impacts). For instance, Simion et al. (2013) developed the mechanism of assessing environmental impacts of C&D waste. Marzouk and Azab (2014) evaluated the economic and environmental impacts of two alternatives (i.e., recycling or disposing) for C&D waste management. Sou et al. (2016) evaluated impacts of current and potential C&D waste management scenarios from environmental, economic, social and regulatory perspectives. Duran et al. (2006) assessed the impact of subsidies and environmental taxes on the financial viability of C&D waste recycling.
- *Assessing the life cycle energy and resource efficiency of processing C&D waste.* Life cycle energy or resource efficiency of C&D waste has been investigated in various countries, such as European Union (Rivero et al., 2016), Spain (Mercante et al., 2012), Italy (Blengini and Garbarino, 2010; Vitale et al., 2017), USA (Diyamandoglu and Fortuna, 2015), and China (Wang et al., 2018; Wu et al., 2015). In terms of the resource efficiency of C&D waste, Mercader and Ramirez (2013) quantified the consumption of materials during the construction stage of residential buildings, and Spoerri et al. (2009) proposed strategic planning for C&D waste recycling in Switzerland according to expert-based scenarios.

The introduction of LCA to C&D waste research is a step up from only viewing the impacts of final disposal of C&D waste. The life cycle thinking for C&D waste research provides a more comprehensive understanding on the impacts of C&D waste management particularly the methods to address the waste (i.e., reuse, recycling, energy recovery, and landfilling). However, the development of life cycle database for C&D waste still lacks even in developed countries, which would limit the adoption of LCA in C&D waste.

3.4. Improving C&D waste management — from a management science perspective

A wide range of topics has been identified from the perspective of management science, with the ultimate purpose of managing and minimizing C&D waste. Each of the topics is discussed as below.

3.4.1. Quantifying the generation of C&D waste

Waste generation has been a hot topic in C&D waste research over the period. Those studies can be generally divided into three categories, i.e., surveying C&D waste generation in specific region, investigating waste generation rates and estimating C&D waste generation through various models. A considerable number of studies were conducted to survey waste generation in specific countries/regions, such as USA (Cochran et al., 2007), Norway (Bergsdal et al., 2007a,b), Malaysia (Lau et al., 2008), Spain (Solis-Guzman et al., 2009), Portugal (Coelho and de Brito, 2011) and China (Wu et al., 2016a; Zheng et al., 2017). Data for estimating waste generation are mainly through methods of site interview, questionnaire, site visits, and observation.

Given that there are various types of construction projects inducing waste, waste generation rate is regarded as a critical indicator to C&D waste generation. The rationale for developing this indicator is that the average amount of waste generated in the same type of projects is normally of small variation (Li et al., 2013; Lu et al., 2011, 2017; Malia et al., 2013). As for the estimation of C&D waste via models, Kern et al. (2015) proposed a model to estimate C&D waste in high-rise buildings following multiple regression approach. Won et al. (2016) proposed an approach to estimate the amount of C&D waste avoided through Building Information Modelling (BIM) oriented design. Wu et al. (2016b) developed a method to predict the amount of demolition waste at the city level with the aid of the Geographic Information System (GIS). Although traditional methods (e.g., site interview, questionnaire, site visits, and observation) are dominantly used, it is observed that new approaches have been developed in recent years.

3.4.2. C&D waste reduction via management measures

Waste reduction/minimisation is a fundamental goal to manage C&D waste. The C&D waste management situations in different countries have been investigated with a primary aim of diverting waste building materials from landfills, such as in UK (Ajayi et al., 2016), Turkey (Esin and Cosgun, 2007), Malaysia (Begum et al., 2007), China (Tam and Tam, 2008). Apart from the concrete C&D waste reduction measures in design, construction, operation, and demolition of projects, human factors and economic incentives to reduce C&D waste were discussed by prior literature.

- *Understanding human factors in C&D waste management.* Human factors in C&D waste management have attracted increasing attention. This is because the attitudes and behaviour of stakeholders can significantly affect the effectiveness of practices of C&D waste management (Lu and Yuan, 2010). In the context of Palestinian territory, Al-Sari et al. (2012) examined the potential impacts of behaviours and attitudes on the performance of waste management. Udawatta et al. (2015b) investigated stakeholders' attitudes and behaviours on waste management in Australia and consequently identified ways for improving the waste management practices. Tam and Hao (2016) investigated attitudes of the Toronto construction industry towards recycling on construction sites. Wu et al. (2017) examined the critical factors to contractor's behaviour in terms of managing C&D waste in mainland China. Yuan et al. (2018) identified factors influencing project managers' behavioural intentions to reduce

C&D waste. All these literature confirmed the importance of human factors in affecting the management of C&D waste.

- *C&D waste disposal charging scheme.* The effectiveness of C&D waste disposal charging scheme is regarded as critical in minimizing waste generation at source. In Hong Kong, the disposal of C&D waste has emerged as a crucial problem because of limited land resources for waste landfills as destination of final disposal (Poon et al., 2013), which resulted in serial studies examining the effectiveness and impacts of C&D waste disposal charging scheme (Hao et al., 2008; Yu et al., 2013). Recently this issue has attracted attention in mainland China. For example, Yuan and Wang (2014) developed a system dynamics model to explore an appropriate waste disposal charging fee in south China.

3.4.3. Economic feasibility of C&D waste recycling

C&D waste management, particularly the recycling of C&D waste forms an integral part of the circular economy. Several studies have been made to examine the economic feasibility of C&D waste recycling given that a primary drive for stakeholders to implement waste recycling lies in the economic benefits of waste recycling (Begum et al., 2006; Coelho and de Brito, 2013; Jung et al., 2015; Zhao et al., 2010). Their findings showed that recycling of C&D is economically feasible and plays an important role in the improvement of environmental management (Begum et al., 2006). However, the recycling costs would be significantly influenced by the transport distance, the construction site conditions, and the amount of waste to be recycled (Jung et al., 2015). One of the difficulties in conducting valid studies to examine the feasibility of C&D waste recycling is to define the appropriate system boundary, because the different setting of the system boundary would change the results dramatically. The assumption made in such studies sometimes is unrealistic in the real world; for instance, the C&D waste materials cannot always be treated on time, and the recycled products cannot always be traded at the targeted prices, which would influence the outcome of evaluating the economic feasibility.

3.5. Reducing C&D waste — from architecture, engineering, construction and operation of buildings perspective

As C&D waste generation is determined by the activities in design, construction, renovation, maintenance, and demolition, some research efforts have been made from the disciplines of architecture, engineering, construction, and operation of buildings.

3.5.1. Reducing C&D waste from design

Main factors that affect the minimisation of C&D waste reduction are examined by relating to specific project stages. Design, for example, is a critical stage to implement waste minimisation as considering the detail of construction projects can prevent unnecessary design change and overconsumption of materials (Osmani et al., 2008). Wang et al. (2014) identified critical enablers to effective waste minimisation during the design phase, particularly design changes. Although researchers have been aware that design plays a crucial role in affecting C&D waste generation, reducing C&D waste through design is not widely discussed in prior literature. Architects did not view C&D waste as a priority in the design process (Osmani et al., 2008). This is mainly because there is a lack of practical approaches to evaluate the effect of better design on reducing C&D waste (Wang et al., 2015). Thus, without proven benefits, it is challenging to convince architects to adopt specific design methods for waste minimisation. Hence the value of reducing C&D waste by design is currently overlooked.

3.5.2. Reducing C&D waste during the construction, operation and demolition stages

It is commonly perceived that C&D waste is mainly generated during construction and demolition stages. Significant efforts were made on reducing C&D waste on construction sites (Poon et al., 2004; Hao et al., 2008; Wang et al., 2010). Particularly, on-site sorting was recognised as an effective way to reduce waste and increase reuse and recycling (Poon et al., 2001; Wang et al., 2010). More recently, renovation and maintenance of buildings were identified as essential sources of C&D waste, although the waste generation is at a smaller scale compared with construction and demolition (Cheng and Ma, 2013; Lu et al., 2016). Many recommendations have been proposed to reduce C&D waste in prior studies; however, one remaining problem is the lack of meaningful methods to assess the effectiveness of waste management activities. Only if they are proven useful, the proposed waste reduction methods in prior studies can be applied to the practice.

4. Mainstreams of C&D waste research: future directions

Following the critical analysis of developed theories and concepts of C&D waste research, the preliminary achievements in the selected samples were identified. Based on these achievements, we analysed the strengths/weaknesses and knowledge gaps. By combining the existing knowledge in the field and highlighting what has been done, what has not been done, and how it can be done, the future research agenda is then formulated (see Fig. 2).

4.1. Research opportunities in studying C&D waste from environmental science and environmental engineering perspectives

There are significant progress such as the identification of pollutant composition, control and mitigation of pollution, and environmental impact assessment methods. Based on the review, research opportunities are identified as follows.

4.1.1. Identifying pollutants in C&D waste generated from industrial buildings

It has been discussed frequently that C&D waste may contain heavy metals (Jang and Townsend, 2001; Van Praagh and Modin, 2016) and organic matter (Duan et al., 2016). The main focus of such studies is the C&D waste generated from residential, commercial buildings and civic projects, while C&D waste in landfills or treatment facilities may come from demolished industrial buildings such as abandoned pesticide manufacturing plant, which can cause pollution or toxicity to the environment. The composition and properties of these C&D wastes are very complex, and mixed hazardous substances would have multi-path risks (Huang et al., 2016, 2017). Although the portion of these hazardous substances in total C&D waste is relatively small, the environmental harms could be significantly severe. This issue has been revealed recently and thus deserves more research efforts. Hence, in the future, it is suggested to investigate pollutants in the C&D waste from industrial buildings.

4.1.2. Developing comprehensive pollutant control measures for treating C&D waste

Previous studies have suggested that C&D waste would result in environmental pollution to water (Ferguson and Male, 1980), groundwater (Lee et al., 2008; Suh, 2004) and soils (Cabalar et al., 2016; Kalbe et al., 2008). Significant efforts have been made to control the pollution of C&D waste to water and soils on construction sites and landfills. The processing of C&D waste may lead to other issues such as air pollution (e.g., particulate matter) and noise pollution, which were largely overlooked in prior studies. It is

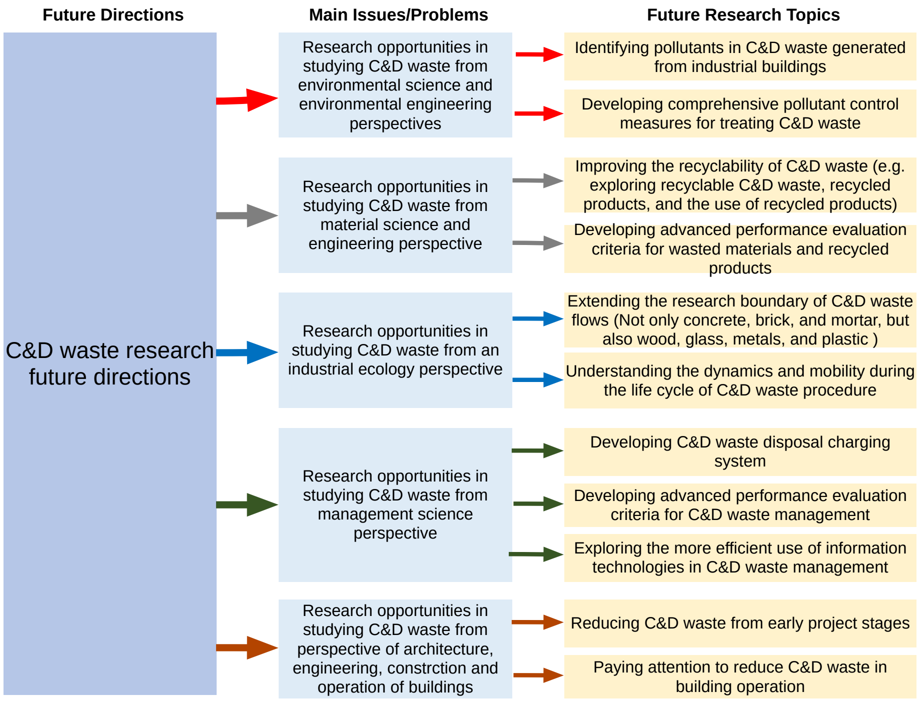


Fig. 2. Future research directions for C&D waste.

noticed that particulate matter would be generated during various stages of C&D waste treatment, e.g., waste generation, on-site sorting, transportation, and crushing. Similarly, these activities would cause noise pollution to the surrounding environment due to machinery operation. Thus, more comprehensive pollutant control measures for C&D waste should be taken into consideration when investigating C&D waste treatment.

4.2. Research opportunities in studying C&D waste from material science and engineering perspective

The recycling of C&D waste has attracted wide attention from scholars in material science and engineering disciplines. Following the existed hot topics such as recycling aggregate and concrete, the study identifies some future directions, including improving the recyclability of C&D waste and the development of performance evaluation criteria.

4.2.1. Improving the recyclability of C&D waste

Significant studies have been carried out to develop recycled products applications such as recycled aggregate, recycled fine aggregate, recycled sand, recycled glass, hot mix asphalt from recycled concrete, cement mortar, sand and glass waste (Arulrajah et al., 2014; Garcia-Gonzalez et al., 2014; Gomez-Meijide et al., 2016; Kang and Kee, 2017; Tam et al., 2007). The use of recycled products made from C&D waste has been extensively discussed, where these recycled products are used in road base (Xuan et al., 2016) or pavement subbase (Arulrajah et al., 2013). Rarely few effects have been made to explore the recyclability related issues of C&D waste, such as glass, timber, and plastic, although these materials are essential compositions of C&D waste and account for a considerable portion. Meanwhile, the application of recycled C&D waste products is limited to certain situations mainly in the use of road base/subbase. In this case, the recycling of multiple C&D waste materials and the use of recycled products could be further explored in future studies. For instance, recycled sand blends in prefabricated concrete, the timber used in land re-habitations, soil improvement, and urban development.

4.2.2. Developing advanced performance evaluation criteria for wasted materials and recycled products

Previous studies assessed the performance of waste materials and recycled products from various aspects, typically including: behaviour, thermal performance, mechanical properties, physical properties, engineering properties, mechanical behaviour, permanent deformation and curing conditions (Corinaldesi and Moriconi, 2009; Silva et al., 2015b; Belagraa et al., 2017; Tam et al., 2015b). In order to assess the performance of waste materials and recycled products, these indicators have been frequently used (e.g., strength, compressive strength, bond strength, durability, stiffness, porosity, conductivity, microstructure, density, elasticity, modulus of elasticity, hardened properties) (Correia et al., 2006; Dantas et al., 2013; Younis and Pilakoutas, 2013). Although there are technical standards for certain recycled products such as recycled aggregate and recycled concrete, there is a lack of discussion on systematic and practical performance evaluation criteria for waste materials and recycled products. A better understanding of the performance of wasted materials and recycled products can boost the development of C&D waste recycling. Hence, the development of advanced performance evaluation criteria can be essential in future studies.

4.3. Research opportunities in studying C&D waste from an industrial ecology perspective

Emphasising on the material flows, life cycle impacts and dynamics of C&D waste treatment industry, significant studies have been carried out from an industrial ecology perspective. We identify research opportunities from the following aspects within this theme.

4.3.1. Extending the research boundary of C&D waste flows

Several studies tracked the mass flow or material flow of C&D waste, and assessed the life cycle energy and resource efficiency of C&D waste (Huang and Hsu, 2003; Blengini and Garbarino, 2010; Hiete et al., 2011; Wiedenhofer et al., 2015), but they mainly focused on C&D waste materials such as concrete, brick, and mortar (Zheng et al., 2017). Apart from these materials, C&D waste consists of numerous valuable materials including wood, glass, metals, and plastic. Meanwhile, the mixed C&D waste may contain hazardous components (e.g., asbestos) that have severe impacts on human health, the natural environment and the society (Roussat et al., 2008; Gualtieri, 2013). These small fractions of C&D waste were generally overlooked in most waste management systems mainly due to their less significant scale, as well as they are hard to be sorted out. To better understand the character of C&D waste flows, extending the research boundary of C&D waste flows to understand how multiple C&D waste flows from generation to final disposal would be worth for further investigations.

4.3.2. Understanding the dynamics and mobility during the life cycle of C&D waste procedure

It is well recognised that the C&D waste treatment should be considered as a system (Dosho, 2007; Yuan and Wang, 2014). However, earlier studies have viewed the C&D waste processing as an isolated activity. Prior studies have identified that dynamics is a critical feature of the C&D waste recycling system particularly in the new era that requires higher recycling level (Yuan and Wang, 2014). More recently, driven by the economic incentive, C&D waste would be transported from one region to the other, considering the significant cost difference of waste recycling and disposal among various regions. However, previous studies have treated the C&D waste processing as a local-closed issue. This is mainly decided by the nature of C&D waste, heavyweight and low unit economic value, which makes the transport of C&D waste cost inefficient. Therefore, it is imperative to rethink the dynamics and mobility in processing C&D waste.

4.4. Research opportunities in studying C&D waste from the management science perspective

As a critical management activity, C&D waste raised wide attention from the management science point of view. The study proposes some potential topics for future studies.

4.4.1. Developing C&D waste disposal charging system

As discussed earlier, the waste disposal charging scheme has drawn significant attention. Some studies quantified the impacts of waste disposal charging scheme on C&D waste management (Hao et al., 2008; Poon et al., 2013), while some studies attempted to determine an appropriate waste disposal charging fee for better waste reduction (Yuan and Wang, 2014). However, these studies mainly investigated the disposal charging fee at the city level. Significantly different disposal charging fees between cities may trigger the cross-regional mobility of C&D waste and cross-border illegal dumping. Hence, a systematic C&D waste disposal charging system at regional/national level plays a critical role to improve the performance of waste management, which could be a potential research topic.

4.4.2. Developing advanced performance assessment methods for C&D waste management

One of the purposes of managing C&D waste is to achieve sustainability in the construction industry (Blengini, 2009) and the recycling of C&D waste is viewed as an essential part of the circular economy. To evaluate the effectiveness of C&D waste management, a number of studies have developed various performance assessment approaches based on classical theories, such as life cycle assessment (Kucukvar et al., 2016; Mercante et al., 2012; Wu et al., 2015), economic feasibility and viability (Coelho and de Brito, 2013). However, it is difficult to determine whether a C&D waste management system is effective if only one dimension (e.g., economic) performs well. By examining existing studies, there is a lack of systematic performance assessment approach for evaluating the effectiveness of C&D waste management by integrating environmental, economic and social aspects. Hence, advanced methods which could cover these aspects could be explored in the future.

4.4.3. Exploring the more efficient use of information technologies in C&D waste management

Although information technologies (e.g., GIS, BIM, and Big Data) have been applied in C&D waste research, these technologies are employed as tools for research, rather than improving the actual C&D waste management and recycling practices. For instance, to improve the research accuracy, Wu et al. (2016b) designed a method to estimate the amount of demolition waste and potential recycling value with the aid of GIS, which provides useful inputs for the landfill planning. Wang et al. (2018) integrated LCA and BIM to estimate the carbon emission of building demolition waste. Similarly, big data has been adopted for construction waste analytics (Lu et al., 2015). Bilal et al. (2016) developed a conceptual framework following the big data approach for the assessment of waste management performance.

Limited studies applied BIM to improve the actual C&D waste management activities. Instead, most of the existing studies focused on minimizing waste generation at the design phase through the BIM application. For instance, Baldwin et al. (2008) employed BIM to assess how waste could be reduced in high rise residential buildings via the prefabrication-oriented design. Porwal and Hewage (2012) conducted a BIM-based analysis to minimise the waste rate of structural reinforcement. Won and Cheng (2017) further highlighted the potential of using BIM in C&D waste management, mainly on the design coordination and measurement of quantities. Hence, more studies are required in the future to enhance the efficiency of information technology applications in improving C&D waste management practices.

4.5. Research opportunities in studying C&D waste from the perspective of architecture, engineering, construction and operation of buildings

Apart from the demolition, the design, construction, and operation of buildings also generate considerable C&D waste. Based on the review, we identify several research opportunities.

4.5.1. Reducing C&D waste from early project stages

Waste reduction/minimisation is a critical goal of managing

C&D waste. Several studies introduced methods to reduce C&D waste ranging from construction sites to landfills in different countries (Tam and Tam, 2008). Apart from the construction and demolition stages, project design stage and on-site waste sorting stage have been identified as two stages that significantly affect the effectiveness of C&D waste management (Wang et al., 2014). For instance, the adoption of prefabrication in the design process would dramatically change the management of C&D waste in building construction (Li et al., 2014; Tam et al., 2015a,b). Due to limited research focusing on this issue, practitioners like architects did not view C&D waste issue as a priority in project design. Therefore, future research opportunity exists to investigate how the planning of early project stages, particularly the design stage would influence C&D waste management.

4.5.2. Reducing C&D waste in building operation

Significant studies have been undertaken to minimise the generation of C&D waste during construction. By contrast, very few studies have paid attention to waste generated in the renovation of buildings which has been recently identified as a critical source of waste (Cheng and Ma, 2013; Lu et al., 2016). This is arguably due to the fact that the generation of renovation and maintenance waste is difficult to track, and the compositions of generated waste vary dramatically among projects. For such an inevitable problem in C&D waste management, future studies are suggested to better understand the growing waste generated in building operation, such as revealing the waste generation and composition, and developing effective waste reduction measures.

5. Conclusions

To examine the status quo of C&D waste research and propose future research agenda, the study systematically reviewed C&D waste related articles that have been published in major sources (WoS, Scopus, and Google Scholar) since the 1990s. This study reveals that C&D waste has been investigated from various disciplines including environmental science and environmental engineering, material science and engineering, industrial ecology perspective, management science, and architecture, engineering, construction and operation of buildings. Findings show that the focus of C&D waste research varies significantly according to the aforementioned disciplines. In particular, researchers from environmental science and environmental engineering discipline usually consider C&D waste as a kind of solid waste, while studies from material science and engineering field and management science field usually recognise C&D waste as a crucial issue in the construction industry. Researchers from environmental science and environmental engineering, and material science and engineering fields consider C&D waste as a subject (i.e., waste or product), while studies from industrial ecology and management science fields tend to examine C&D waste issue from a system perspective.

Through the critical review, future research opportunities including 11 research topics are identified.

- Research opportunities which exist in studying C&D waste from environmental science and environmental engineering perspective include (1) identifying pollutants in C&D waste generated from industrial buildings, and (2) developing comprehensive pollutant control measures to treat C&D waste.
- Research opportunities which exist in studying C&D waste from a material science and engineering perspective include (1) improving the recyclability of C&D waste, and (2) developing advanced performance evaluation criteria for wasted materials and recycled products.
- Research opportunities in studying C&D waste from an industrial ecology perspective include (1) extending the research boundary of C&D waste flows, and (2) understanding the dynamics and mobility during the life cycle of C&D waste management.
- Research opportunities which exist in studying C&D waste from management science perspective include (1) developing appropriate C&D waste disposal charging system, (2) developing advanced performance assessment methods for C&D waste management, and (3) exploring the more efficient use of information technologies in C&D waste management.
- Research opportunities in studying C&D waste from the perspective of architecture, engineering, construction and operation of buildings include (1) reducing C&D waste from early project stages, and (2) reducing C&D waste during the building operation.

The study provides an in-depth insight into the body of knowledge of C&D waste, which offers a useful reference for scholars to explore the future research opportunities. Meanwhile, the information contained in the study can assist the practitioners to improve the recycling and management of C&D waste, as well as mitigate pollution from C&D waste.

Acknowledgements

The authors wish to acknowledge the financial support from the National Natural Science Foundation of China (71573216), Adelaide Scholarship International (ASI-1712146), the Sichuan Science and Technology Program (2017ZR0150), and the Shenzhen Science and Technology Plan (No. JCYJ20160520173631894).

References

Abanda, F.H., Tah, J.H.M., Cheung, F.K.T., 2013. Mathematical modelling of embodied energy, greenhouse gases, waste, time–cost parameters of building projects: a review. Build. Environ. 59, 23–37. https://doi.org/10.1016/j.buildenv.2012.07.014.

Ajayi, S.O., Oyedele, L.O., Akinade, O.O., Bilal, M., Owolabi, H.A., Alaka, H.A., Kadiri, K.O., 2016. Reducing waste to landfill: a need for cultural change in the UK construction industry. J. Build Eng. 5, 185–193. https://doi.org/10.1016/j.jobe.2015.12.007.

Ajayi, S.O., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A., Owolabi, H.A., Kadiri, K.O., 2015. Waste effectiveness of the construction industry: understanding the impediments and requisites for improvements. Resour. Conserv. Recycl. 102, 101–112. https://doi.org/10.1016/j.resconrec.2015.06.001.

Al-Sari, M.I., Al-Khatib, I.A., Avraamides, M., Fatta-Kassinos, D., 2012. A study on the attitudes and behavioural influence of construction waste management in Occupied Palestinian Territory. Waste Manag. Res. 30 (2), 122–136. https://doi.org/10.1177/0734242x11423066.

Anastasiou, E., Filikas, K.G., Stefanidou, M., 2014. Utilization of fine recycled aggregates in concrete with fly-ash and steel slag. Constr. Build. Mater. 50, 154–161. https://doi.org/10.1016/j.conbuildmat.2013.09.037.

Arulrajah, A., Ali, M.M.Y., Disfani, M.M., Horpibulsuk, S., 2014. Recycled-glass blends in pavement base/subbase applications: laboratory and field evaluation. J. Mater. Civ. Eng. 26 (7), 12. https://doi.org/10.1061/(asce)mt.1943-5533.0000966.

Arulrajah, A., Piratheepan, J., Disfani, M.M., Bo, M.W., 2013. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. J. Mater. Civ. Eng. 25 (8), 1077–1088. https://doi.org/10.1061/(asce)mt.1943-5533.0000652.

Baldwin, A.N., Shen, L.Y., Poon, C.S., Austin, S.A., Wong, I., 2008. Modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings. Autom. ConStruct. 17 (3), 333–341. https://doi.org/10.1016/j.autcon.2007.05.013.

Begum, R.A., Siwar, C., Pereira, J.J., Jaafar, A.H., 2006. A benefit-cost analysis on the economic feasibility of construction waste minimisation: the case of Malaysia. Resour. Conserv. Recycl. 48 (1), 86–98. https://doi.org/10.1016/j.resconrec.2006.01.004.

Begum, R.A., Siwar, C., Pereira, J.J., Jaafar, A.H., 2007. Implementation of waste management and minimisation in the construction industry of Malaysia. Resour. Conserv. Recycl. 51 (1), 190–202. https://doi.org/10.1016/j.resconrec.2006.09.004.

Belagraa, L., Beddar, M., Bouzid, A., 2017. Mabble fillers effect on the mechanical

performance of a recycled aggregate concrete. Environ. Eng. Manag. J. 16 (1), 197–204.
Bergersen, O., Haarstad, K., 2014. Treating landfill gas hydrogen sulphide with mineral wool waste (MWW) and rod mill waste (RMW). Waste Manag. 34 (1), 141–147. https://doi.org/10.1016/j.wasman.2013.09.012.
Bergsdal, H., Bohne, R.A., Brattebo, H., 2007a. Projection of construction and demolition waste in Norway. J. Ind. Ecol. 11 (3), 27–39. https://doi.org/10.1162/jiec.2007.1149.
Bergsdal, H., Brattebo, H., Bohne, R.A., Mueller, D.B., 2007b. Dynamic material flow analysis for Norway's dwelling stock. Build. Res. Inf. 35 (5), 557–570. https://doi.org/10.1080/09613210701287588.
Bernardo, M., Gomes, M.C., de Brito, J., 2016. Demolition waste generation for development of a regional management chain model. Waste Manag. 49, 156–169. https://doi.org/10.1016/j.wasman.2015.12.027.
Bilal, M., Oyedele, L.O., Akinade, O.O., Ajayi, S.O., Alaka, H.A., Owolabi, H.A., et al., 2016. Big data architecture for construction waste analytics (CWA): a conceptual framework. J. Build Eng. 6, 144–156. https://doi.org/10.1016/j.jobe.2016.03.002.
Bjegovic, D., Stirmer, N., Serdar, M., 2012. Durability properties of concrete with blended cements. Mater. Corros. Werkstoffe Korrosion 63 (12), 1087–1096. https://doi.org/10.1002/maco.201206699.
Blengini, G.A., 2009. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Build. Environ. 44 (2), 319–330.
Blengini, G.A., Garbarino, E., 2010. Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. J. Clean. Prod. 18 (10–11), 1021–1030. https://doi.org/10.1016/j.jclepro.2010.01.027.
Boote, D.N., Beile, P., 2005. Scholars before researchers: on the centrality of the dissertation literature review in research preparation. Educ. Res. 34 (6), 3–15.
Bravo, M., de Brito, J., Pontes, J., Evangelista, L., 2015. Durability performance of concrete with recycled aggregates from construction and demolition waste plants. Constr. Build. Mater. 77, 357–369. https://doi.org/10.1016/j.conbuildmat.2014.12.103.
Cabalar, A.F., Abdulnafaa, M.D., Karabash, Z., 2016. Influences of various construction and demolition materials on the behavior of a clay. Environ. Earth Sci. 75 (9), 9. https://doi.org/10.1007/s12665-016-5631-4.
Cheng, J.C., Ma, L.Y., 2013. A BIM-based system for demolition and renovation waste estimation and planning. Waste Manag. 33 (6), 1539–1551.
Choudhary, A., Shah, V., Bishnoi, S., 2016. Effect of low cost fillers on cement hydration. Constr. Build. Mater. 124, 533–543. https://doi.org/10.1016/j.conbuildmat.2016.07.088.
Cochran, K., Townsend, T., Reinhart, D., Heck, H., 2007. Estimation of regional building-related C&D debris generation and composition: case study for Florida, US. Waste Manag. 27 (7), 921–931. https://doi.org/10.1016/j.wasman.2006.03.023.
Coelho, A., de Brito, J., 2011. Generation of construction and demolition waste in Portugal. Waste Manag. Res. 29 (7), 739–750. https://doi.org/10.1177/0734242x11402253.
Coelho, A., de Brito, J., 2013. Economic viability analysis of a construction and demolition waste recycling plant in Portugal - part I: location, materials, technology and economic analysis. J. Clean. Prod. 39, 338–352. https://doi.org/10.1016/j.jclepro.2012.08.024.
Corinaldesi, V., Moriconi, G., 2009. Behaviour of cementitious mortars containing different kinds of recycled aggregate. Constr. Build. Mater. 23 (1), 289–294. https://doi.org/10.1016/j.conbuildmat.2007.12.006.
Correia, J.R., de Brito, J., Pereira, A.S., 2006. Effects on concrete durability of using recycled ceramic aggregates. Mater. Struct. 39 (2), 169–177. https://doi.org/10.1617/s11527-005-9014-7.
da Silva, V.M., Gois, L.C., Duarte, J.B., da Silva, J.B., Acchar, W., 2014. Incorporation of ceramic waste into binary and ternary soil-cement formulations for the production of solid bricks. Mater. Res. Ibero-Am. J. Mater. 17 (2), 326–331. https://doi.org/10.1590/s1516-14392014005000014.
Dantas, A.T.A., Leite, M.B., Nagahama, K.D., 2013. Prediction of compressive strength of concrete containing construction and demolition waste using artificial neural networks. Constr. Build. Mater. 38, 717–722. https://doi.org/10.1016/j.conbuildmat.2012.09.026.
Delay, M., Lager, T., Schulz, H.D., Frimmel, F.H., 2007. Comparison of leaching tests to determine and quantify the release of inorganic contaminants in demolition waste. Waste Manag. 27 (2), 248–255. https://doi.org/10.1016/j.wasman.2006.01.013.
Denyes, M.J., Parisien, M.A., Rutter, A., Zeeb, B.A., 2014. Physical, chemical and biological characterization of six biochars produced for the remediation of contaminated sites. J. Vis. Exp. (93), 1–12. https://doi.org/10.3791/52183.
Diyamandoglu, V., Fortuna, L.M., 2015. Deconstruction of wood-framed houses: material recovery and environmental impact. Resour. Conserv. Recycl. 100, 21–30. https://doi.org/10.1016/j.resconrec.2015.04.006.
Dosho, Y., 2007. Development of a sustainable concrete waste recycling system - application of recycled aggregate concrete produced by aggregate replacing method. J. Adv. Concr. Technol. 5 (1), 27–42. https://doi.org/10.3151/jact.5.27.
Duan, H., Yu, D.F., Zuo, J., Yang, B., Zhang, Y.K., Niu, Y.N., 2016. Characterization of brominated flame retardants in construction and demolition waste components: HBCD and PBDEs. Sci. Total Environ. 572, 77–85. https://doi.org/10.1016/j.scitotenv.2016.07.165.
Duran, X., Lenihan, H., O'Regan, B., 2006. A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland. Resour. Conserv. Recycl. 46 (3), 302–320. https://doi.org/10.1016/j.resconrec.2005.08.003.
Engelsen, C.J., van der Sloot, H.A., Petkovic, G., 2017. Long-term leaching from recycled concrete aggregates applied as sub-base material in road construction. Sci. Total Environ. 587, 94–101. https://doi.org/10.1016/j.scitotenv.2017.02.052.
Erkman, S., 1997. Industrial ecology: an historical view. J. Clean. Prod. 5 (1–2), 1–10.
Esa, M.R., Halog, A., Rigamonti, L., 2017. Strategies for minimizing construction and demolition wastes in Malaysia. Resour. Conserv. Recycl. 120, 219–229. https://doi.org/10.1016/j.resconrec.2016,12.014.
Esin, T., Cosgun, N., 2007. A study conducted to reduce construction waste generation in Turkey. Build. Environ. 42 (4), 1667–1674. https://doi.org/10.1016/j.buildenv.2006.02.008.
European Commission, 2017. Construction and demolition waste, waste streams, environment. avaliable at. http://ec.europa.eu/environment/waste/construction_demolition.htm.
Evangelista, L., de Brito, J., 2017. Flexural behaviour of reinforced concrete beams made with fine recycled concrete aggregates. J. Civ. Eng. 21 (1), 353–363. https://doi.org/10.1007/s12205-016-0653-8.
Falagas, M.E., Pitsouni, E.I., Malietzis, G.A., Pappas, G., 2008. Comparison of PubMed, Scopus, web of science, and Google scholar: strengths and weaknesses. FASEB J. 22 (2), 338–342.
Ferguson, D.W., Male, J.W., 1980. The water-polltion potential from demolition waste-disposal. J. Environ. Sci. Health A Environ. Sci. Eng. 15 (6), 545–559.
Galvin, A.P., Ayuso, J., Jimenez, J.R., Agrela, F., 2012. Comparison of batch leaching tests and influence of pH on the release of metals from construction and demolition wastes. Waste Manag. 32 (1), 88–95. https://doi.org/10.1016/j.wasman.2011.09.010.
Gao, D.Y., Zhang, L., Nokken, M., 2017. Mechanical behavior of recycled coarse aggregate concrete reinforced with steel fibers under direct shear. Cement Concr. Compos. 79, 1–8. https://doi.org/10.1016/j.cemconcomp.2017.01.006.
Garcia-Gonzalez, J., Rodriguez-Robles, D., Juan-Valdes, A., Moran-del Pozo, J.M., Guerra-Romero, M.I., 2014. Pre-saturation technique of the recycled aggregates: solution to the water absorption drawback in the recycled concrete manufacture. Materials 7 (9), 6224–6236. https://doi.org/10.3390/ma7096224.
Gomes, P.C.C., Ulsen, C., Pereira, F.A., Quattrone, M., Angulo, S.C., 2015. Comminution and sizing processes of concrete block waste as recycled aggregates. Waste Manag. 45, 171–179. https://doi.org/10.1016/j.wasman.2015.07.008.
Gomez-Meijide, B., Perez, I., Pasandin, A.R., 2016. Recycled construction and demolition waste in Cold Asphalt Mixtures: evolutionary properties. J. Clean. Prod. 112, 588–598. https://doi.org/10.1016/j.jclepro.2015.08.038.
Gomez-Meijide, B., Perez, I., Airey, G., Thom, N., 2015. Stiffness of cold asphalt mixtures with recycled aggregates from construction and demolition waste. Constr. Build. Mater. 77, 168–178. https://doi.org/10.1016/j.conbuildmat.2014.12.045.
Grant, M.J., Booth, A., 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. Health Inf. Libr. J. 26 (2), 91–108.
Gualtieri, A.F., 2013. Recycling asbestos-containing material (ACM) from construction and demolition waste (CDW). In: Handbook of Recycled Concrete and Demolition Waste, pp. 500–525.
Hao, J.L., Hills, M.J., Tam, V.W.Y., 2008. The effectiveness of Hong Kong's construction waste disposal charging scheme. Waste Manag. Res. 26 (6), 553–558. https://doi.org/10.1177/0734242x07085345.
Hiete, M., Stengel, J., Ludwig, J., Schultmann, F., 2011. Matching construction and demolition waste supply to recycling demand: a regional management chain model. Build. Res. Inf. 39 (4), 333–351. https://doi.org/10.1080/09613218.2011.576849.
Ho, N.Y., Lee, Y.P.K., Lim, W.F., Zayed, T., Chew, K.C., Low, G.L., Ting, S.K., 2013. Efficient utilization of recycled concrete aggregate in structural concrete. J. Mater. Civ. Eng. 25 (3), 318–327. https://doi.org/10.1061/(asce)mt.1943-5533.0000587.
Hou, Y.Q., Ji, X.P., Zou, L., Liu, S., Su, X.L., 2016. Performance of cement-stabilised crushed brick aggregates in asphalt pavement base and subbase applications. Road Mater. Pavement Des. 17 (1), 120–135. https://doi.org/10.1080/14680629.2015.1064466.
Hu, M.M., van der Voet, E., Huppes, G., 2010. Dynamic material flow analysis for strategic construction and demolition waste management in beijing. J. Ind. Ecol. 14 (3), 440–456. https://doi.org/10.1111/j.1530-9290.2010.00245.x.
Huang, S.L., Hsu, W.L., 2003. Materials flow analysis and emergy evaluation of Taipei's urban construction. Landsc. Urban Plan. 63 (2), 61–74. https://doi.org/10.1016/s0169-2046(02)00152-4.
Huang, S., Zhao, X., Sun, Y.Q., Ma, J.L., Gao, X.F., Xie, T., et al., 2016. Spatial distribution of organic pollutants in industrial construction and demolition waste and their mutual interaction on an abandoned pesticide manufacturing plant. Environ. Sci. Process. Impact 18 (4), 482–492. https://doi.org/10.1039/c6em00019c.
Huang, S., Zhao, X., Sun, Y.Q., Ma, J.L., Gao, X.F., Xie, T., et al., 2017. Pollution of hazardous substances in industrial construction and demolition wastes and their multi-path risk within an abandoned pesticide manufacturing plant. Front. Environ. Sci. Eng. 11 (1), 13. https://doi.org/10.1007/s11783-017-0901-2.
Iden, S.C., Delay, M., Frimmel, F.H., Durner, W., 2008. Assessing contaminant mobilization from waste materials: application of Bayesian parameter estimation to batch extraction tests at varying liquid-to-solid ratios. Environ. Sci. Technol. 42 (10), 3717–3723. https://doi.org/10.1021/es702171z.
Jain, P., Powell, J., Tolaymat, T., 2015. Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States. U.S. Environmental Protection Agency, Washington, DC. EPA/600/R-15/111, 2015.

Jang, Y.C., Townsend, T.G., 2001. Occurrence of organic pollutants in recovered soil fines from construction and demolition waste. Waste Manag. 21 (8), 703–715. https://doi.org/10.1016/s0956-053x(01)00007-1.
Johnson, C.A., Moench, H., Brandenberger, S., 1999. Assessing the potential long-term behavior of the landfill fraction of sorted demolition wastes. J. Environ. Qual. 28 (4), 1061–1067.
Jung, J.S., Song, S.H., Jun, M.H., Park, S.S., 2015. A comparison of economic feasibility and emission of carbon dioxide for two recycling processes. J. Civ. Eng. 19 (5), 1248–1255. https://doi.org/10.1007/s12205-015-0708-2.
Kalbe, U., Berger, W., Eckardt, J., Simon, F.G., 2008. Evaluation of leaching and extraction procedures for soil and waste. Waste Manag. 28 (6), 1027–1038. https://doi.org/10.1016/j.wasman.2007.03.008.
Kanellopoulos, A., Nicolaides, D., Petrou, M.F., 2014. Mechanical and durability properties of concretes containing recycled lime powder and recycled aggregates. Constr. Build. Mater. 53, 253–259. https://doi.org/10.1016/j.conbuildmat.2013.11.102.
Kang, H., Kee, S.H., 2017. Improving the quality of mixed recycled coarse aggregates from construction and demolition waste using heavy media separation with Fe3O4 suspension. Adv. Mater. Sci. Eng. 1–12. https://doi.org/10.1155/2017/8753659.
Karavezyris, V., 2007. Report: treatment of commercial, construction and demolition waste in North Rhine-Westphalia: policy-making and operation options. Waste Manag. Res. 25 (2), 183–189. https://doi.org/10.1177/0734242x07075249.
Kern, A.P., Dias, M.F., Kulakowski, M.P., Gomes, L.P., 2015. Waste generated in high-rise buildings construction: a quantification model based on statistical multiple regression. Waste Manag. 39, 35–44. https://doi.org/10.1016/j.wasman.2015.01.043.
Kralj, D., 2009. Experimental study of recycling lightweight concrete with aggregates containing expanded glass. Process Saf. Environ. Prot. 87 (4), 267–273. https://doi.org/10.1016/j.psep.2009.03.003.
Kruger, O., Kalbe, U., Berger, W., Simon, F.G., Meza, S.L., 2012. Leaching experiments on the release of heavy metals and PAH from soil and waste materials. J. Hazard Mater. 207, 51–55. https://doi.org/10.1016/j.jhazmat.2011.02.016.
Kucukvar, M., Egilmez, G., Tatari, O., 2014. Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life-cycle analysis. Waste Manag. Res. 32 (6), 500–508. https://doi.org/10.1177/0734242x14536457.
Kucukvar, M., Egilmez, G., Tatari, O., 2016. Life cycle assessment and optimization-based decision analysis of construction waste recycling for a LEED-certified university building. Sustainability 8 (1), 13. https://doi.org/10.3390/su8010089.
Kumar, R., 2017. Influence of recycled coarse aggregate derived from construction and demolition waste (CDW) on abrasion resistance of pavement concrete. Constr. Build. Mater. 142, 248–255. https://doi.org/10.1016/j.conbuildmat.2017.03.077.
Lau, H.H., Whyte, A., Law, P.L., 2008. Composition and characteristics of construction waste generated by residential housing project. Int. J. Environ. Res. 2 (3), 261–268.
Lee, J.Y., Moon, S.H., Yi, M.J., Yun, S.T., 2008. Groundwater contamination with petroleum hydrocarbons, chlorinated solvents and high pH: implications for multiple sources. Q. J. Eng. Geol. Hydrogeol. 41, 35–47. https://doi.org/10.1144/1470-9236/07-021.
Leite, F.D., Motta, R.D., Vasconcelos, K.L., Bernucci, L., 2011. Laboratory evaluation of recycled construction and demolition waste for pavements. Constr. Build. Mater. 25 (6), 2972–2979. https://doi.org/10.1016/j.conbuildmat.2010.11.105.
Li, J.R., Ding, Z.K., Mi, X.M., Wang, J.Y., 2013. A model for estimating construction waste generation index for building project in China. Resour. Conserv. Recycl. 74, 20–26. https://doi.org/10.1016/j.resconrec.2013.02.015.
Li, J.X., Yang, E.H., 2017. Macroscopic and microstructural properties of engineered cementitious composites incorporating recycled concrete fines. Cement Concr. Compos. 78, 33–42. https://doi.org/10.1016/j.cemconcomp.2016.12.013.
Li, Z.D., Shen, G.Q., Alshawi, M., 2014. Measuring the impact of prefabrication on construction waste reduction: An empirical study in China. Resour. Conserv. Recycl. 91, 27–39. https://doi.org/10.1016/j.resconrec.2014.07.013.
Lovato, P.S., Possan, E., Dal Molin, D.C.C., Masuero, A.B., Ribeiro, J.L.D., 2012. Modeling of mechanical properties and durability of recycled aggregate concretes. Constr. Build. Mater. 26 (1), 437–447. https://doi.org/10.1016/j.conbuildmat.2011.06.043.
Lu, W.S., Yuan, H.P., 2010. Exploring critical success factors for waste management in construction projects of China. Resour. Conserv. Recycl. 55 (2), 201–208. https://doi.org/10.1016/j.resconrec.2010.09.010.
Lu, W.S., Chen, X., Ho, D.C.W., Wang, H.D., 2016. Analysis of the construction waste management performance in Hong Kong: the public and private sectors compared using big data. J. Clean. Prod. 112, 521–531. https://doi.org/10.1016/j.jclepro.2015.06.106.
Lu, W.S., Chen, X., Peng, Y., Shen, L.Y., 2015. Benchmarking construction waste management performance using big data. Resour. Conserv. Recycl. 105, 49–58. https://doi.org/10.1016/j.resconrec.2015.10.013.
Lu, W.S., Yuan, H.P., Li, J.R., Hao, J.J.L., Mi, X.M., Ding, Z.K., 2011. An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. Waste Manag. 31 (4), 680–687. https://doi.org/10.1016/j.wasman.2010.12.004.
Lu, W., Yuan, H., 2011. A framework for understanding waste management studies in construction. Waste Manag. 31 (6), 1252–1260. https://doi.org/10.1016/j.wasman.2011.01.018.
Lu, W., Webster, C., Peng, Y., Chen, X., Zhang, X., 2017. Estimating and calibrating the amount of building-related construction and demolition waste in urban China. Int. J. Constr. Manag. 17 (1), 13–24.
Lye, C.-Q., Dhir, R.K., Ghataora, G.S., Li, H., 2016. Creep strain of recycled aggregate concrete. Constr. Build. Mater. 102, 244–259. https://doi.org/10.1016/j.conbuildmat.2015.10.181.
Malia, M., de Brito, J., Pinheiro, M.D., Bravo, M., 2013. Construction and demolition waste indicators. Waste Manag. Res. 31 (3), 241–255. https://doi.org/10.1177/0734242x12471707.
Marzouk, M., Azab, S., 2014. Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. Resour. Conserv. Recycl. 82, 41–49. https://doi.org/10.1016/j.resconrec.2013.10.015.
Matias, D., de Brito, J., Rosa, A., Pedro, D., 2013. Mechanical properties of concrete produced with recycled coarse aggregates - influence of the use of superplasticizers. Constr. Build. Mater. 44, 101–109. https://doi.org/10.1016/j.conbuildmat.2013.03.011.
Mercader-Moyano, P., Ramirez-de-Arellano-Agudo, A., 2013. Selective classification and quantification model of C&D waste from material resources consumed in residential building construction. Waste Manag. Res. 31 (5), 458–474. https://doi.org/10.1177/0734242x13477719.
Mercante, I.T., Bovea, M.D., Ibanez-Fores, V., Arena, A.P., 2012. Life cycle assessment of construction and demolition waste management systems: a Spanish case study. Int. J. Life Cycle Assess. 17 (2), 232–241. https://doi.org/10.1007/s11367-011-0350-2.
Meyer, C., 2009. The greening of the concrete industry. Cement Concr. Compos. 31 (8), 601–605. https://doi.org/10.1016/j.cemconcomp.2008.12.010.
Miranda, L.F.R., Constantino, C.S., Monich, C.R., Neto, A.A.D., 2013. Use of recycled sand produced at construction sites in bedding mortars. J. Mater. Civ. Eng. 25 (2), 236–242. https://doi.org/10.1061/(asce)mt.1943-5533.0000593.
Miranda, L.F.R., Lapenda, M.P., Teixeira, S.H.C., Vogt, V., 2014. Rational procedure for composition of screed mortar with recycled sand at a construction site. J. Mater. Civ. Eng. 26 (5), 855–862. https://doi.org/10.1061/(asce)mt.1943-5533.0000877.
Mongeon, P., Paul-Hus, A., 2016. The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics 106 (1), 213–228.
Nassar, A.I., Mohammed, M.K., Thom, N., Parry, T., 2016. Mechanical, durability and microstructure properties of Cold Asphalt Emulsion Mixtures with different types of filler. Constr. Build. Mater. 114, 352–363. https://doi.org/10.1016/j.conbuildmat.2016.03.112.
Osmani, M., Glass, J., Price, A.D., 2008. Architects' perspectives on construction waste reduction by design. Waste Manag. 28 (7), 1147–1158.
Oygard, J.K., Gjengedal, E., Mage, A., 2005. Mass-balance estimation of heavy metals and selected anions at a landfill receiving MSWI bottom ash and mixed construction wastes. J. Hazard Mater. 123 (1–3), 70–75. https://doi.org/10.1016/j.jhazmat.2005.04.022.
Park, J., Tucker, R., 2017. Overcoming barriers to the reuse of construction waste material in Australia: a review of the literature. Int. J. Constr. Manag. 17 (3), 228–237.
Pasandin, A.R., Perez, I., 2013. Laboratory evaluation of hot-mix asphalt containing construction and demolition waste. Constr. Build. Mater. 43, 497–505. https://doi.org/10.1016/j.conbuildmat.2013.02.052.
Pasandin, A.R., Perez, I., 2014. Mechanical properties of hot-mix asphalt made with recycled concrete aggregates coated with bitumen emulsion. Constr. Build. Mater. 55, 350–358. https://doi.org/10.1016/j.conbuildmat.2014.01.053.
Penacho, P., de Brito, J., Veiga, M.R., 2014. Physico-mechanical and performance characterization of mortars incorporating fine glass waste aggregate. Cement Concr. Compos. 50, 47–59. https://doi.org/10.1016/j.cemconcomp.2014.02.007.
Poon, C.S., Ann, T.W., Ng, L.H., 2001. On-site sorting of construction and demolition waste in Hong Kong. Resour. Conserv. Recycl. 32 (2), 157–172.
Poon, C.S., Yu, A.T.W., Wong, A., Yip, R., 2013. Quantifying the impact of construction waste charging scheme on construction waste management in Hong Kong. J. Constr. Eng. Manag. 139 (5), 466–479. https://doi.org/10.1061/(asce)co.1943-7862.0000631.
Poon, C.S., Yu, A.T., Jaillon, L., 2004. Reducing building waste at construction sites in Hong Kong. Constr. Manag. Econ. 22 (5), 461–470.
Porwal, A., Hewage, K.N., 2012. Building information modeling-based analysis to minimize waste rate of structural reinforcement. J. Constr. Eng. Manag. 138 (8), 943–954. https://doi.org/10.1061/(asce)co.1943-7862.0000508.
Rafi, M.M., Qadir, A., Ali, S., Siddiqui, S.H., 2014. Performance of hot mix asphalt mixtures made of recycled aggregates. J. Test. Eval. 42 (2), 357–367. https://doi.org/10.1520/jte20130004.
Randolph, J.J., 2009. A guide to writing the dissertation literature review. Pract. Assess. Res. Eval. 14 (13), 1–13.
Rivero, A.J., Sathre, R., Navarro, J.G., 2016. Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. Resour. Conserv. Recycl. 108, 171–181. https://doi.org/10.1016/j.resconrec.2016.01.014.
Roussat, N., Mehu, J., Abdelghafour, M., Brula, P., 2008. Leaching behaviour of hazardous demolition waste. Waste Manag. 28 (11), 2032–2040. https://doi.org/10.1016/j.wasman.2007.10.019.
Shin, E., Kang, J., 2015. Migration of calcium hydroxide compounds in construction waste soil. Adv. Environ. Res. An. Int. J. 4 (3), 183–196. https://doi.org/10.12989/aer.2015.4.3.183.
Shin, W.S., Na, K.R., Kim, Y.K., 2016. Adsorption of metal ions from aqueous solution by recycled aggregate: estimation of pretreatment effect. Desalination Water. Treat. 57 (20), 9366–9374. https://doi.org/10.1080/19443994.2015.1029528.
Silva, R.V., de Brito, J., Dhir, R.K., 2014. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete

production. Constr. Build. Mater. 65, 201–217. https://doi.org/10.1016/j.conbuildmat.2014.04.117.
Silva, R.V., de Brito, J., Dhir, R.K., 2015a. Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete. Eng. Struct. 100, 31–42. https://doi.org/10.1016/j.engstruct.2015.06.004.
Silva, R.V., de Brito, J., Dhir, R.K., 2015b. Tensile strength behaviour of recycled aggregate concrete. Constr. Build. Mater. 83, 108–118. https://doi.org/10.1016/j.conbuildmat.2015.03.034.
Sim, J., Park, C., 2011. Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. Waste Manag. 31 (11), 2352–2360. https://doi.org/10.1016/j.wasman.2011.06.014.
Simion, I.M., Ghinea, C., Maxineasa, S.G., Taranu, N., Bonoli, A., Gavrilescu, M., 2013. Ecological footprint applied in the assessment of construction and demolition waste integrated management. Environ. Eng. Manag. J. 12 (4), 779–788.
Solis-Guzman, J., Marrero, M., Montes, M.V., Ramirez-De-Arellano, A., 2009. A Spanish model for quantification and management of construction waste. Waste Manag. 29 (9), 2542–2548. https://doi.org/10.1016/j.wasman.2009.05.009.
Sou, W.I., Chu, A., Chiueh, P.T., 2016. Sustainability assessment and prioritisation of bottom ash management in Macao. Waste Manag. Res. 34 (12), 1275–1282. https://doi.org/10.1177/0734242x16665914.
Soutsos, M., Fulton, M.C., 2016. Recycling of demolition waste in Merseyside. Proc. Inst. Civ. Eng. Constr. Mater. 169 (2), 54–66. https://doi.org/10.1680/coma.15.00012.
Spoerri, A., Lang, D.J., Binder, C.R., Scholz, R.W., 2009. Expert-based scenarios for strategic waste and resource management planning-C&D waste recycling in the Canton of Zurich, Switzerland. Resour. Conserv. Recycl. 53 (10), 592–600. https://doi.org/10.1016/j.resconrec.2009.04.011.
Stefanidou, M., Anastasiou, E., Filikas, K.G., 2014. Recycled sand in lime-based mortars. Waste Manag. 34 (12), 2595–2602. https://doi.org/10.1016/j.wasman.2014.09.005.
Suh, J.Y., 2004. Hydrogeochemical studies of groundwater from reclaimed land adjacent to Rozelle Bay, Sydney, Australia. Geosci. J. 8 (3), 301–312. https://doi.org/10.1007/bf02910249.
Tam, V.W.Y., 2008. On the effectiveness in implementing a waste-management-plan method in construction. Waste Manag. 28 (6), 1072–1080. https://doi.org/10.1016/j.wasman.2007.04.007.
Tam, V.W.Y., Hao, J.J.L., 2016. Attitudes towards recycling on construction sites. Proc. Inst. Civ. Eng. Waste Resour. Manag. 169 (3), 6. https://doi.org/10.1680/jwarm.15.00006.
Tam, V.W.Y., Tam, C.M., 2009. Parameters for assessing recycled aggregate and their correlation. Waste Manag. Res. 27 (1), 52–58. https://doi.org/10.1177/0734242x07079875.
Tam, V.W.Y., Fung, I.W.H., Sing, M.C.P., Ogunlana, S.O., 2015a. Best practice of prefabrication implementation in the Hong Kong public and private sectors. J. Clean. Prod. 109, 216–231. https://doi.org/10.1016/j.jclepro.2014.09.045.
Tam, V.W.Y., Kotrayothar, D., Xiao, J.Z., 2015b. Long-term deformation behaviour of recycled aggregate concrete. Constr. Build. Mater. 100, 262–272. https://doi.org/10.1016/j.conbuildmat.2015.10.013.
Tam, V.W.Y., Tam, C.M., Le, K.N., 2007. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resour. Conserv. Recycl. 50 (1), 82–101. https://doi.org/10.1016/j.resconrec.2006.05.012.
Tam, V.W., Tam, C.M., 2008. Waste reduction through incentives: a case study. Build. Res. Inf. 36 (1), 37–43. https://doi.org/10.1080/09613210701417003.
Tam, V.W., Soomro, M., Evangelista, A.C.J., 2018. A review of recycled aggregate in concrete applications (2000–2017). Constr. Build. Mater. 172, 272–292.
Udawatta, N., Zuo, J., Chiveralls, K., Zillante, G., 2015a. Attitudinal and behavioural approaches to improving waste management on construction projects in Australia: benefits and limitations. Int. J. Constr. Manag. 15 (2), 137–147. https://doi.org/10.1080/15623599.2015.1033815.
Udawatta, N., Zuo, J., Chiveralls, K., Zillante, G., 2015b. Improving waste management in construction projects: an Australian study. Resour. Conserv. Recycl. 101, 73–83. https://doi.org/10.1016/j.resconrec.2015.05.003.
Ulsen, C., Kahn, H., Hawlitschek, G., Masini, E.A., Angulo, S.C., John, V.M., 2013. Production of recycled sand from construction and demolition waste. Constr. Build. Mater. 40, 1168–1173. https://doi.org/10.1016/j.conbuildmat.2012.02.004.
Van Praagh, M., Modin, H., 2016. Leaching of chloride, sulphate, heavy metals, dissolved organic carbon and phenolic organic pesticides from contaminated concrete. Waste Manag. 56, 352–358. https://doi.org/10.1016/j.wasman.2016.07.009.
Vegas, I., Broos, K., Nielsen, P., Lambertz, O., Lisbona, A., 2015. Upgrading the quality of mixed recycled aggregates from construction and demolition waste by using near-infrared sorting technology. Constr. Build. Mater. 75, 121–128. https://doi.org/10.1016/j.conbuildmat.2014.09.109.
Vieira, T., Alves, A., de Brito, J., Correia, J.R., Silva, R.V., 2016. Durability-related performance of concrete containing fine recycled aggregates from crushed bricks and sanitary ware. Mater. Des. 90, 767–776. https://doi.org/10.1016/j.matdes.2015.11.023.
Vitale, P., Arena, N., Di Gregorio, F., Arena, U., 2017. Life cycle assessment of the end-of-life phase of a residential building. Waste Manag. 60, 311–321. https://doi.org/10.1016/j.wasman.2016.10.002.
Wang, J.Y., Li, Z.D., Tam, V.W.Y., 2014. Critical factors in effective construction waste minimization at the design stage: a Shenzhen case study, China. Resour. Conserv. Recycl. 82, 1–7. https://doi.org/10.1016/j.resconrec.2013.11.003.
Wang, J.Y., Yuan, H.P., Kang, X.P., Lu, W.S., 2010. Critical success factors for on-site sorting of construction waste: a China study. Resour. Conserv. Recycl. 54 (11), 931–936. https://doi.org/10.1016/j.resconrec.2010.01.012.
Wang, J., Li, Z., Tam, V.W., 2015. Identifying best design strategies for construction waste minimization. J. Clean. Prod. 92, 237–247.
Wang, J., Wu, H., Duan, H., Zillante, G., Zuo, J., Yuan, H., 2018. Combining Life Cycle Assessment and Building Information Modelling to account for carbon emission of building demolition waste: a case study. J. Clean. Prod. 172, 3154–3166.
Warren, J.D., Chong, W.K., Kim, C., 2007. Recycling construction and demolition waste for construction in Kansas City metropolitan area, Kansas and Missouri. Transp. Res. Rec. 2011, 193–200. https://doi.org/10.3141/2011-21.
Webster, J., Watson, R.T., 2002. Analyzing the past to prepare for the future: writing a literature review. MIS Q. 13–23.
Wehrer, M., Totsche, K.U., 2008. Effective rates of heavy metal release from alkaline wastes - quantified by column outflow experiments and inverse simulations. J. Contam. Hydrol. 101 (1–4), 53–66. https://doi.org/10.1016/j.jconhyd.2008.07.005.
Wiedenhofer, D., Steinberger, J.K., Eisenmenger, N., Haas, W., 2015. Maintenance and expansion modeling material stocks and flows for residential buildings and transportation networks in the EU25. J. Ind. Ecol. 19 (4), 538–551. https://doi.org/10.1111/jiec.12216.
Won, J., Cheng, J.C.P., 2017. Identifying potential opportunities of building information modeling for construction and demolition waste management and minimization. Autom. ConStruct. 79, 3–18. https://doi.org/10.1016/j.autcon.2017.02.002.
Won, J., Cheng, J.C.P., Lee, G., 2016. Quantification of construction waste prevented by BIM-based design validation: case studies in South Korea. Waste Manag. 49, 170–180. https://doi.org/10.1016/j.wasman.2015.12.026.
Wu, H.Y., Duan, H.B., Wang, J.Y., Wang, T., Wang, X.F., 2015. Quantification of carbon emission of construction waste by using streamlined LCA: a case study of Shenzhen, China. J. Mater. Cycles Waste Manag. 17 (4), 637–645. https://doi.org/10.1007/s10163-015-0404-9.
Wu, H.Y., Duan, H.B., Zheng, L.N., Wang, J.Y., Niu, Y.N., Zhang, G.M., 2016a. Demolition waste generation and recycling potentials in a rapidly developing flagship megacity of South China: prospective scenarios and implications. Constr. Build. Mater. 113, 1007–1016. https://doi.org/10.1016/j.conbuildmat.2016.03.130.
Wu, H.Y., Wang, J.Y., Duan, H.B., Ouyang, L., Huang, W.K., Zuo, J., 2016b. An innovative approach to managing demolition waste via GIS (geographic information system): a case study in Shenzhen city, China. J. Clean. Prod. 112, 494–503. https://doi.org/10.1016/j.jclepro.2015.08.096.
Wu, Z.Z., Yu, A.T.W., Shen, L.Y., 2017. Investigating the determinants of contractor's construction and demolition waste management behavior in Mainland China. Waste Manag. 60, 290–300. https://doi.org/10.1016/j.wasman.2016.09.001.
Wu, Z., Yu, A.T.W., Shen, L., Liu, G., 2014. Quantifying construction and demolition waste: an analytical review. Waste Manag. 34 (9), 1683–1692. https://doi.org/10.1016/j.wasman.2014.05.010.
Xuan, D.X., Molenaar, A.A.A., Houben, L.J.M., 2016. Shrinkage cracking of cement treated demolition waste as a road base. Mater. Struct. 49 (1–2), 631–640. https://doi.org/10.1617/s11527-015-0524-7.
Xue, C.Z., Shen, A.Q., Guo, Y.C., He, T.Q., 2016. Utilization of construction waste composite powder materials as cementitious materials in small-scale prefabricated concrete. Adv. Mater. Sci. Eng. 1–11. https://doi.org/10.1155/2016/8947935.
Yeheyis, M., Hewage, K., Alam, M.S., Eskicioglu, C., Sadiq, R., 2013. An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability. Clean Technol. Environ. Policy 15 (1), 81–91. https://doi.org/10.1007/s10098-012-0481-6.
Younis, K.H., Pilakoutas, K., 2013. Strength prediction model and methods for improving recycled aggregate concrete. Constr. Build. Mater. 49, 688–701. https://doi.org/10.1016/j.conbuildmat.2013.09.003.
Yu, A.T.W., Poon, C.S., Wong, A., Yip, R., Jaillon, L., 2013. Impact of construction waste disposal charging scheme on work practices at construction sites in Hong Kong. Waste Manag. 33 (1), 138–146. https://doi.org/10.1016/j.wasman.2012.09.023.
Yuan, H.P., Wang, J.Y., 2014. A system dynamics model for determining the waste disposal charging fee in construction. Eur. J. Oper. Res. 237 (3), 988–996. https://doi.org/10.1016/j.ejor.2014.02.034.
Yuan, H., Shen, L., 2011. Trend of the research on construction and demolition waste management. Waste Manag. 31 (4), 670–679. https://doi.org/10.1016/j.wasman.2010.10.030.
Yuan, H., Wu, H., Zuo, J., 2018. Understanding factors influencing project managers' behavioral intentions to reduce waste in construction projects. J. Manag. Eng. 34 (6), 04018031.
Zega, C.J., Villagran-Zaccardi, Y.A., Di Maio, A.A., 2010. Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. Mater. Struct. 43 (1–2), 195–202. https://doi.org/10.1617/s11527-009-9480-4.
Zhao, W., Leeftink, R.B., Rotter, V.S., 2010. Evaluation of the economic feasibility for the recycling of construction and demolition waste in China-The case of Chongqing. Resour. Conserv. Recycl. 54 (6), 377–389. https://doi.org/10.1016/j.resconrec.2009.09.003.
Zheng, L.N., Wu, H.Y., Zhang, H., Duan, H.B., Wang, J.Y., Jiang, W.P., Song, Q.B., 2017. Characterizing the generation and flows of construction and demolition waste in China. Constr. Build. Mater. 136, 405–413. https://doi.org/10.1016/j.conbuildmat.2017.01.055.
Zopounidis, C., Doumpos, M., 2002. Multicriteria classification and sorting methods: a literature review. Eur. J. Oper. Res. 138 (2), 229–246.

Appendix E: Published paper in *Resources, Conservation and Recycling*

Statement of Authorship

Title of Paper	A review of performance assessment methods for construction and demolition waste management
Publication Status	[X] Published [ ] Accepted for Publication [ ] Submitted for Publication [ ] Unpublished and Unsubmitted work written in manuscript style
Publication Details	Wu, H., Zuo, J., Yuan, H., Zillante, G., & Wang, J. (2019). A review of performance assessment methods for construction and demolition waste management. *Resources, Conservation and Recycling*, 150, 104407. https://doi.org/10.1016/j.resconrec.2019.104407.

Principal Author

Name of Principal Author (Candidate)	Huanyu Wu		
Contribution to the Paper	Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft		
Overall percentage (%)	60%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	05/05/2020

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Jian Zuo		
Contribution to the Paper	Supervision, Conceptualisation, Methodology, Writing - review & editing, Validation		
Signature		Date	7/5/2020

Name of Co-Author	Hongping Yuan		
Contribution to the Paper	Visualisation, Methodology, Writing - review & editing		
Signature		Date	07/05/2020

Name of Co-Author	George Zillante		
Contribution to the Paper	Supervision, Writing - review & editing		
Signature		Date	7/5/2020

Name of Co-Author	Jiayuan Wang		
Contribution to the Paper	Supervision, Writing – review & editing.		
Signature		Date	07/05/2020

Resources, Conservation & Recycling 150 (2019) 104407

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

A review of performance assessment methods for construction and demolition waste management

Huanyu Wu[a], Jian Zuo[a,b], Hongping Yuan[c,*], George Zillante[a], Jiayuan Wang[b]

[a] *School of Architecture and Built Environment, The University of Adelaide, SA 5001, Australia*
[b] *College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, 518060, PR China*
[c] *School of Management, Guangzhou University, Guangzhou, Guangdong, 510006, PR China*

ARTICLE INFO

Keywords:
Construction and demolition waste
Waste management
Performance assessment methods
System thinking
Life cycle assessment

ABSTRACT

Significant efforts have been devoted to assessing construction and demolition waste management (CDWM). However, there is little knowledge to understand the utilisation of the developed models for assessing CDWM performance, thus limiting the comparison and generalization of recognized methods and tools. By reviewing the prior published literature, this study assesses the current research methods, in particular, data collection. It also reviews the range of critical indicators for CDWM performance assessment considered by the literature and put forwards a new framework for better assessing CDWM performance. The proposed framework summarises the system boundary, research scale and performance assessment aspects documented by previous studies, and further integrate an integrated framework with procedures for better assessing CDWM performance. The literature review found that while some studies adopt a system thinking and life cycle thinking to assess CDWM performance, other research they adopt a sustainability based model to finalize CDWM performance assessment. The results also demonstrate that compared with environmental and economic aspects, the social aspect has attracted less attention. Social factors, however are crucial in CDWM. The findings about current performance assessment practices in CDWM and the proposed procedures are possible to implement for researchers and practitioners to develop sound CDWM approaches.

1. Introduction

As a by-product of construction, renovation and demolition activities, construction and demolition (C&D) waste has become one of the most significant waste flows, which accounts for 30%–40% of the total urban waste generation (Wang et al., 2018). Some major countries generate around 10 billion tonnes of C&D waste annually. Among this, China contributes approximately 3 billion tonnes due to its large-scale urbanization and urban renewal programs (Zheng et al., 2017); while the EU and the US generate more than 800 million tonnes (EC, 2016) and 700 million tonnes (Jain et al., 2016), respectively. The vast generation of C&D waste causes a series of adverse impacts on society and environment, such as land occupation, raw material consumption, energy consumption, greenhouse gas emissions, and water pollution (Poon et al., 2013; Ding et al., 2016a,b; Wang et al., 2018).

How to address C&D waste problems have raised concerns from economic, environmental and societal perspectives (Yuan, 2013). If a system that is capable of dealing with the waste effectively, it should be proposed based on appropriate assessments on the economic, environmental and societal impacts associated with the generated C&D waste (Yuan, 2013). In such assessments, human health and safety have been recognised as the primary concerns (Chung and Lo, 2003); economic efficiency has significant effects on the performance of a waste management system (Begum et al., 2006; Shen et al., 2009; Zhao et al., 2011). Along with the enhancement of the sustainability concept, social and environmental impacts have been highlighted in assessing construction and demolition waste management (CDWM) performance (Klang et al., 2003; Manowong, 2012). As an essential aspect of improving CDWM performance, how to evaluate the effectiveness of the waste management system has become a critical issue (Yuan, 2013).

As a result, several efforts have been made to assess CDWM performance, though the studies have been conducted from different perspectives with various models (Ajayi et al., 2015; Saez et al., 2013; Tam, 2008). For instance, some studies developed their sustainability assessment models to assess CDWM performance, mostly focusing on economic feasibility which is a significant concern of project stakeholders (Begum et al., 2006; Zhao et al., 2010; Jung et al., 2015). Some studies investigated CDWM performance from a holistic view by

* Corresponding author.
E-mail address: hpyuan2005@gmail.com (H. Yuan).

https://doi.org/10.1016/j.resconrec.2019.104407
Received 20 March 2019; Received in revised form 23 June 2019; Accepted 3 July 2019
0921-3449/

simultaneously covering economic aspect (Ye et al., 2012; Zhao et al., 2011), environmental aspect (Ding et al., 2016a,b; Marzouk and Azab, 2014) and social aspect (Yuan, 2012). In these studies, the CDWM system can be defined from different levels (i.e. the project level, the regional level). There are also some other studies assessing different CDWM activities during the life cycle, particularly from the environmental perspective (Ortiz et al., 2010; Butera et al., 2015; Mercante et al., 2012; Penteado and Rosado, 2016; Wang et al., 2018).

However, given various perspectives and methods for assessing CDWM, no study has attempted to provide an in-depth review by systematically examining main methods, models and outcomes in related studies. This would limit the further application of the developed methods and models for improving CDWM practices. In this regard, we aim to present a review of performance assessment methods for CDWM. Such a study would merit existing literature in multiple aspects. Firstly, given the fact that reasonable CDWM performance assessment is an important aspect of developing a robust waste management system, such an in-depth review would be crucial in developing assessment models and methods of more robustness. Secondly, a well-developed framework can be valuable and helpful for researchers who are looking to assess CDWM performance (Lu and Yuan, 2011). Finally, the review can also provide practitioners and policymakers with a comprehensive understanding of the significance and complexity of environmental, economic and social impacts of CDWM, which would be valuable form them to improve the practices,.

Therefore, driven by the practical demand of calling for an effective method to assess CDWM performance, this paper aims to reveal an in-depth understanding of studies on CDWM performance assessment. We intend to answer a research question: how does the CDWM performance be assessed in previous studies? We will summarise the models for assessing CDWM performance, covering research methods, data collection methods, and critical indicators for assessment. Based on the in-depth review, a framework with procedures for assessing CDWM performance will be proposed. A graphical abstract of the study is provided in the Appendix (see Fig. A1).

The remainder of the paper is organized as follows: Section 2 introduces the process of review sample selection; Section 3 analyses the main methods for assessing CDWM performance; Section 4 discusses critical indicators for assessing CDWM performance, followed by a framework for CDWM performance assessment in Section 5; and the concluding remarks are drawn in Section 6.

2. Selection of review samples

A four-step sample selection strategy is adopted to identify the most related papers, i.e., selecting the database; initial searching; selecting the sample; and refining the sample. The procedure of selecting review samples is shown in Fig. 1.

(1) Selecting the database. Several databases can be used to index academic publications, such as Scopus, PubMed, Web of Science, and Google Scholar. An initial comparison found that the Web of Science contained most of CDWM related journals (Lu and Yuan, 2011; Yuan and Shen, 2011), and papers in this database are most accessible and widely used for researchers. Meanwhile, Google Scholar is also a convenient tool to assist sample selection due to its timely-updated data. Hence, the Web of Science was used as the major searching database, and Google Scholar was used as the assistant to further refine the sample.
(2) Initial searching. By typing the keywords "construction waste, demolition waste, construction and demolition waste, C&D waste" in the Web of Science Core Collection database, it initially returned 1,027 C&D waste related papers over the last two decades (until 1 st March 2018). The search only covered articles published in English in databases such as SCI-expanded, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, and CCR-expanded.
(3) Selecting the sample. As the initial searching results include all C&D waste related papers, it is necessary to exclude studies irrelevant to the understanding of CDWM performance assessment. Through an individual reading-selecting procedure, only the CDWM performance assessment related papers have been selected. Within this procedure, the titles and abstracts of the identified paper have been examined. If it is difficult to determine whether the paper is related to the determined issue, the researcher have had to read thought the whole paper. Though time consuming but rigorous, 33 articles highly related to CDWM performance assessment were finally selected. These papers mainly appeared on C&D waste research related journals, such as *Resources Conservation and Recycling*, *Waste Management*, *Journal of Cleaner Production*, *Waste Management Research*, *Journal of Construction Engineering and Management*, and *International Journal of Life Cycle Assessment*.
(4) Refining the sample. Google Scholar was employed to timely update of the sample. Keywords "performance assessment, management performance, construction waste, demolition waste, construction and demolition waste, C&D waste" were input to the Google Scholar to complement the sample. The last search was carried out on 1 st December 2018. In total, 36 papers were selected for our in-depth review, which is tabulated in Table A1 in the Appendix.

3. Main methods for assessing CDWM performance

By reviewing prior studies, there are three main research streams regarding CDWM performance assessment: sustainability-based methods, system thinking-based methods, and life cycle thinking-based methods. In a large number of prior studies, researchers developed sustainability-based models which employed well-selected indicators to conduct the assessment. Meanwhile, a considerable percentage of previous studies used well-developed methods such as Life Cycle Assessment (LCA) and System Dynamics (SD) for assessment. Fig. 2 shows the distribution of main methods used in prior studies for assessing CDWM performance. In these studies, the selection of indicators varies among different models according to the subjects that the study focuses on, i.e., environmental, economic or social aspects. For instance, the majority of studies adopted LCA mainly concentrate on the environmental aspect due to the nature of the method, though there are studies combined other tools with LCA for more extensive assessments on CDWM. SD, much differently, has a broader targeting on covering various aspects. The section below will discuss the utilization of methodologies in assessing CDWM performance.

3.1. Sustainability-based methods

Sustainability is a favourite topic in CDWM research. These studies are named after keywords such as sustainability (environmental, economic and social performance), economic feasibility and management effectiveness.

3.1.1. Sustainability: economic, environmental and social performance

A significant number of prior studies are defined within the framework of sustainability (i.e., economic, environmental and social sustainability). Some studies developed their sustainability assessment model to assess CDWM performance. In terms of the selection of research priorities, different studies favour different strategies. Some studies developed multi-criteria assessment models covering more than one aspects amongst economic, environmental and social issues (Klang et al., 2003; Kucukvar et al., 2016; Marrero et al., 2017). For instance, Klang et al. (2003) presented a model for evaluating waste management systems' contributions to sustainable development, covering environmental, economic and social aspects. The model was tested through cases in Norway and Sweden regarding the recovery and recycling of C &D waste. While some concentrated on only one aspect, e.g. economic (Wang et al., 2004; Stenis, 2005; Srour et al., 2013), environmental

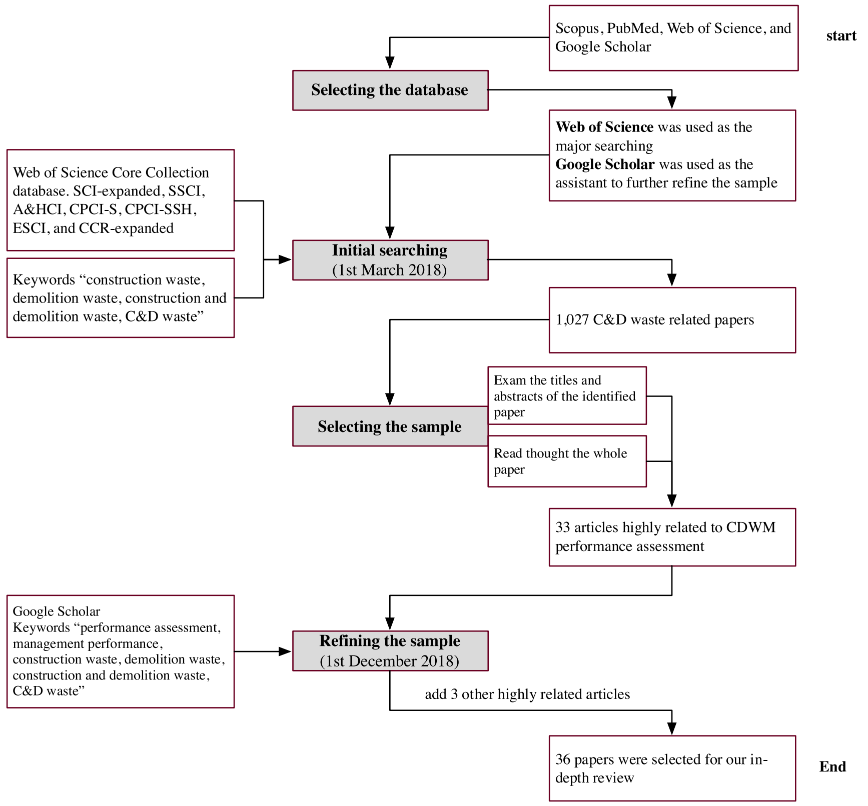


Fig. 1. Sample selection procedure.

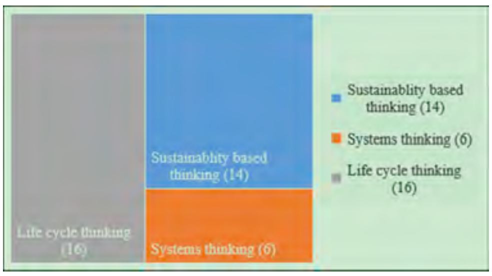


Fig. 2. The distribution of main methods used in prior studies for assessing CDWM performance.

(Roussat et al., 2009; Butera et al., 2015; Ding et al., 2016a,b; Dejkovski, 2016) or social (Yuan, 2012).

Although the priority of these studies are different, they shared some common research procedure. Usually, the first step is to define the research goal and scope. The second is to identify the criteria. The selection of criteria is generally through a literature review according to the study purpose. The third is to quantify the indicators. The final step is to run the model (i.e. calculation), and usually this is based on scenario analysis. The developed models are typically adopted in a case study to validate the proposed model. In most cases, the study would provide quantitative results, while sometimes the study would result in qualitative recommendations (Yuan, 2013b).

3.1.2. Economic feasibility-focused research

In fast-developing countries like China, there are huge demands on C&D waste disposal, and there is a vast market potential for recycled C&D waste products. The recycling of C&D waste is somehow seen as a market activity (Wu et al., 2015). Economic feasibility is frequently mentioned in assessing CDWM performance because it has been a major concern of project stakeholders (Yuan et al., 2018). Many studies have indicated that the CDWM strategies such as waste minimisation, on-site recycling, and centralised recycling would have economic benefits, and these methods are general economic feasible. For instance, Begum et al. (2006) found the waste minimisation is economically feasible by performing a benefit-cost analysis. However, many studies also indicated that the economic feasibility of C&D waste recycling would depend on various factors, such as the economics of scale and the methods of recycling. Duran et al. (2006) suggested that economic viability is likely to occur when the cost of landfilling exceeds the cost of bringing the waste to the recycling centre and the cost of using primary aggregates exceeds the cost of using recycled aggregates. This is mainly because the economies of scale implying that an increase in the size of a centre, in turn, results in a decrease in recycling costs. Moreover, Jung et al. (2015) evaluated the economic feasibility of two recycling processes:

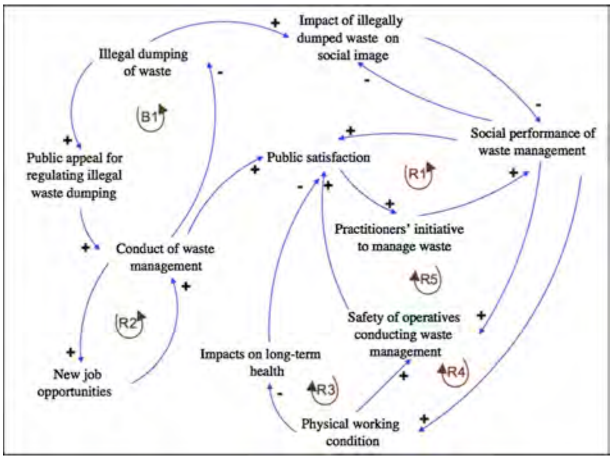


Fig. 3. A causal loop diagram for evaluating CDWM performance. Note: the deeper color indicates the higher research-intensive. (Source: Yuan, 2012).

Table 1
Performance assessment aspects of prior CDWM studies.

	Paper	Region	Keywords	Environmental	Economic	Social
1	(Chung and Lo, 2003)	Hong Kong	Sustainability	√	√	√
2	(Klang et al., 2003)	Norway and Sweden	Sustainability	√	√	√
3	(Begum et al., 2006)	Malaysia	economic feasibility		√	
4	(Duran et al., 2006)	Ireland	economic viability		√	
5	(Bohne et al., 2008)	Norway	eco-efficiency	√	√	
6	(Gomes et al., 2008)	Brazil	N/A	√	√	
7	(Rocha and Sattler, 2009)	Brazil	N/A		√	
8	(Lu et al., 2009)	Hong Kong	Cost efficiency		√	
9	(Roussat et al., 2009)	N/A	sustainability	√		
10	(Shen et al., 2009)	Hong Kong	Benefits		√	
11	(Merino et al., 2010)	Spain	Sustainability	√		
12	(Ortiz et al., 2010)	Spain	Environmental performance	√		
13	(Tam et al., 2010)	Australia, Hong Kong, Japan	Benefits/Difficulties/Recommendation	√	√	
14	(Zhao et al., 2010)	China/Chongqing	Economic feasibility		√	
15	(Yuan et al., 2011)	China/Shanghai	Energy analysis (efficiency)	√	√	
16	(Zhao et al., 2011)	China/Chongqing	economic feasibility		√	
17	(Manowong, 2012)	Thailand	Sustainability	√	√	√
18	(Mercante et al., 2012)	Spain	environmental performance	√		
19	(Ye et al., 2012)	China/Shenzhen	environmental performance	√		
20	(Yuan, 2012)	China/Shenzhen	Social performance			√
21	(Simion et al., 2013)	Italy	Sustainability/Ecological footprint	√		
22	(Srour et al., 2013)	Lebanon	Economic feasibility		√	
23	(Yuan, 2013)	N/A	Effectiveness	√	√	√
24	(Marzouk and Azab, 2014)	Egypt	Environmental and economic impact assessment	√	√	
25	(Tam et al., 2014)	China/Shenzhen	Land occupy	√	√	
26	(Butera et al., 2015)	Denmark	Life cycle assessment	√		
27	(Dahlbo et al., 2015)	Finland	Environmental performance and economic performance	√	√	
28	(Dejkovski, 2016)	Australia	Environmental performance	√		
29	(Ding et al., 2016a,b)	China/Shenzhen	Environmental impacts	√		
30	(Ding et al., 2016a,b)	China/Shenzhen	Environmental performance	√	√	
31	(Kucukvar et al., 2016)	USA	Life cycle assessment	√	√	
32	(Penteado and Rosado, 2016)	Brazil	Life cycle assessment	√		
33	(Zambrana-Vasquez et al., 2016)	Spain	Environmental performance	√		
34	(Chau et al., 2017)	Hong Kong	Environmental performance	√		
35	(Marrero et al., 2017)	Spain	Ecological Footprint and economic impact	√		
36	(Wang et al., 2018)	China/Shenzhen	BIM; LCA	√		

on-site recycling process and process of a private recycling centre. The results told that recycling costs were strongly influenced by the transport distance, the construction site conditions, and the amount of waste concrete to recycle. Hence, the results of economic feasibility assessment might vary under different circumstances.

On the other hand, to enhance the economic viability of C&D waste recycling, some scholars also provide recommendations from various aspects. For instance, Zhao et al. (2010) suggested that economic instruments like the tax that can be adopted in the CDWM to balance the economic viability of C&D waste recycling. Furthermore, economic

Table 2
Methods and indicators for assessing the environmental impacts of CDWM. Environmental impact assessment methods and indicators in CDWM studies (Life cycle thinking).

Authors	(Bohne et al., 2008)	(Ortiz et al., 2010)	(Butera et al., 2015)	(Penteado and Rosado, 2016)	(Chau et al., 2017)	(Wang et al., 2018)
Method	LCA	LCA	LCA	LCA	Life cycle energy assessment	LCA
indicators source	Eco-Indicator 99[a]	CML 2 (baseline 2000)[b]	EASETECH[c]	CML 2 (baseline 2001) [b]	N/A	IPCC 2013 GWP 100a V1.01[d]
Indicators	Damage to resources Damage to ecosystems Damage to human health	Acidification Potential Global Warming Potential Eutrophication Freshwater aquatic Eco toxicity Human Toxicity Terrestrial Eco toxicity Additional: Resources use Renewable energy Non-renewable energy Overall water use	Global warming Photochemical Ozone Formation Particulate mater Terrestrial Acidification Freshwater Eutrophication Marine Eutrophication Terrestrial Eutrophication	Acidification potential Global warming potential Eutrophication potential Photochemical oxidation Depletion of abiotic resources	Energy saving	Carbon emissions
			…			

Note:
a. Eco-indicator 98 is based on the inventory data from the Ecoinvent library and the USA Input Output Database 98;
b. CML is an impact assessment method proposed by Centre of Environmental Science of Leiden University;
c. EASETECH is a model for LCA of waste and energy systems developed by the Technical University of Denmark;
d. IPCC 100 is a characterization model developed by the Intergovernmental Panel on Climate Change for Climate change.

instruments for minimising construction waste can be adopted to promote revenue for environmental policy, encourage waste prevention efforts, discourage the least desirable disposal practices, and avoid the negative consequences of environmental unfriendly treatment and disposal practices Begum et al. (2006). To be concerned that, the effectiveness of policies for improving the economic performance of CDWM can be hardly validated.

3.1.3. Management effectiveness-focused research

How to assess the effectiveness of CDWM is another hot topic in the field, although the definition of the effectiveness of CDWM is yet agreed in the area. At this moment, the management effectiveness-focused research is mainly targeting the development of the concept and the development of indicators to assess the management effectiveness at different levels. Typically, at the project level, Saez et al. (2013) evaluated the effectiveness of 20 best practice measures regarding CDWM, namely the use of industrialized systems, the contract of suppliers managing the waste, and the distributing of small containers in the work areas. At the city level, Tam (2008) investigated the effectiveness of existing waste management methods in the Hong Kong construction industry. In the study, it identified the main benefits gained, the significant difficulties and some useful measures to encourage waste management; Yuan (2013) proposed a framework for assessing the effectiveness of CDWM. It identified 30 key indicators affecting the overall effectiveness of CDWM from a holistic perspective and developed an effective framework for assessing CDWM by integrating identified indicators. At the industry level, Ajayi et al. (2015) explored factors impeding the effectiveness of existing waste management strategies, as well as plans for reducing waste intensiveness of the construction industry. With these achievements in prior exploratory studies, more efforts are called to expand the research on assessing the effectiveness of CDWM in the future.

3.2. System thinking-based methods

System thinking is a holistic analysis approach capable of explaining how a system's constituent parts interrelate and how systems work over time and within the context of larger systems. System dynamics (SD), which was introduced by Jay Forrester in the 1960s, provides useful tools for better understanding those large-scale complex management problems in line with the system thinking principles (Yuan, 2012). It has been a well-established methodology for understanding, studying, visualizing and analysing complex dynamic feedback systems. Usually SD requires constructing the “causal loop diagrams” or “stock and flow diagram” to form a quantitative model for applications (Dyson and Chang, 2005). There are a number of studies employing SD to assess CDWM performance (Zhao et al., 2011; Ye et al., 2012; Yuan, 2012; Marzouk and Azab, 2014; Tam et al., 2014; Ding et al., 2016a,b). In the above applications, five phases, namely problem definition, dynamic hypothesis, simulation model, model testing and policy design, are commonly designed.

3.2.1. Problem definition

The first step is to define the research goal and scope (Yuan, 2012). To optimise the CDWM, previous studies developed SD models to evaluate CDWM performance by integrating economic, environmental and social aspects. The CDWM system can be defined from either from the project level or from the regional level. At the project level, Zhao et al. (2011) evaluated the economic feasibility of choosing C&D waste recycling centres in Chongqing, China. Ye et al. (2012) developed an SD model to assess the environmental performance of CDWM and a new frame-structured building in Shenzhen City, China is chosen as the case study. Yuan (2012) developed an SD model to assess the social performance of CDWM. At the city level, Tam et al. (2014) developed an SD model for CDWM in China. It examined how the landfill charges would affect illegal dumping behaviours. Ding et al. (2016) then

Table 3
Methods and indicators for assessing the environmental impacts of CDWM. Environmental performance assessment indicators in CDWM studies (System thinking).

Authors	(Ye et al., 2012)	(Yuan, 2012)	(Marzouk and Azab, 2014)	(Ding et al., 2016a,b)
Method	SD	SD	SD	SD
indicators source	Case study/literature review	Literature review/interview	Case study	Literature review/ interview
Indicators	Air pollution	Land consumption due to waste landfilling	NOX emissions	Land Resource Index
	Illegally dumping on public living environment	Water pollution	GWP emissions	Water Resource Index
	Noise emission	Noise emission	Energy consumption	Energy Resource Index
	Water quality	Air pollution	Unit land loses from landfills space by C &D waste landfilling	Air Resource Index
		Environmental impacts of illegal waste dumping on public living environment		

examined how changes in sorting behaviours, changes in source reduction measures would influence C&D waste reduction performance. At the national level, Marzouk and Azab (2014) evaluated the impacts of recycling and landfill disposal for CDWM in Egypt.

3.2.2. Dynamic hypothesis

In this step, variables and relationships among variables were structured by a causal loop diagram. The interactions among different variables and loops decide the system's behaviour (Marzouk and Azab, 2014). The identification of variables and variable relationships are confirmed based on literature review (Marzouk and Azab, 2014), interview or a mixed method including above methods (Ding et al., 2016a,b). An example of a causal loop diagram for evaluating the social performance of CDWM is illustrated in Fig. 3 (Yuan, 2012).

3.2.3. Simulation model

In this stage, the variables and the relationships in the causal loop diagram will be quantified and together form the stock and flow diagrams, which is used to quantify the system structure and behaviour. The valuation of variables generally based on multiple methods, including theoretical assumption, experts' estimation, and secondary data (Yuan, 2012). Meanwhile, equations are used to express the interactions among the variables in the model.

3.2.4. Model validations

Once the initial models have been estimated, a series of model tests would be conducted to build the model confidence. The examination of the SD model normally includes five aspects, namely boundary-adequacy test, structure verification tests, dimension consistency test, parameter verification test, and extreme conditions test (Qudrat-Ullah and Seong, 2010). Despite this, the validation of SD model is controversial among many discussions due to the nature of the methodology. Hence, the reliability of SD models would largely depend on the modelling capacity and skills of the researchers.

3.2.5. Policy design

Based on the well-established SD model, the scenario analysis can be conducted to simulate the model and to develop practical implications further. This scenario analysis usually includes single-policy scenarios and multi-policy scenarios. For instance, the changing of the physical working environment and operatives' safety is adopted to simulate the influence on the value of social performance of CDWM separately and collaboratively in a prior study (Yuan, 2012).

3.3. Life cycle thinking-based methods

Life cycle thinking is a widely adopted approach to assess the environmental performance of a product or system. It considers the environmental impacts of a product system 'from the cradle to the grave', which examines the life cycle stages from the raw material extraction, manufacturing, transportation, to use and end-of-life treatment and final disposal (McDougall et al., 2008). Based on the contribution by the Society for Environmental Toxicology and Chemistry (SETAC), the International Standards Organisation (ISO) has further developed the ISO 14040 series on Life Cycle Assessment (LCA). According to ISO 14040, the phases of an LCA consist of four stages, namely goal & scope definition, inventory analysis, impact assessment and interpretation (ISO 14040). However, the ISO standards are defined in a rather vague language, which makes it difficult to assess whether an LCA has been made according to the standard.

LCA has also been applied to quantify and compare potential environmental impacts related to recovery, utilisation, and final disposal of C&D waste materials (Butera et al., 2015). There are a number of studies employing LCA or combining other tools with LCA for more extensive CDWM assessments (Bohne et al., 2008; Chau et al., 2017; Kucukvar et al., 2016; Mercante et al., 2012; Ortiz et al., 2010; Penteado and Rosado, 2016; Simion et al., 2013; Wang et al., 2018; Wu et al., 2015). These studies followed the fundamental structure of LCA provided by ISO 14040 series. Although the contents of these phases vary in different cases, this structure is the basis of all LCA studies. The following contents will showcase how LCA is adopted in CDWM.

3.3.1. Goal & scope definition

The most critical methodological choices, assumptions, and limitations should be clearly described in the first phase. These include the functional unit, initial system boundaries, and criteria for inclusion of inputs and outputs, and dealing with the multifunctional process (Goedkoop et al., 2008). A workable detailed illustration for this can be found in the *Introduction to LCA with SimaPro*. It is found that almost all previous LCA-C&D waste studies choose 1 t of C&D waste consisting of various waste fractions as the functional unit, which is reasonable due to the nature of C&D waste.

In the C&D waste related studies, the setting of system boundary can be summarised according to the following categories (from micro scale to macro scale):

(a) The CDWM of a project. E.g., Ortiz et al. (2010) evaluated environmental impacts of the treatment of construction waste generated from the LIFE 98 ENV/E351 project. Chau et al. (2017) conducted a study on the Lifecycle energy assessment (LCEA) of the End-of-Life phase of a high-rise concrete office buildings in Hong Kong. A typical high-rise residential building in China was selected as the study case (Wang et al., 2018).
(b) The overall CDWM system in a city. E.g., Bohne et al. (2008) evaluated the eco-efficiency of C&D waste recycling system at the city level in Norway; Wu et al. (2015) examined the carbon emission of handling construction waste in China.
(c) The recycling facility for overall C&D waste in a country. E.g., Mercante et al. (2012) compared the environmental performance for two types of C&D waste recycling facilities in Spain. A similar study was carried out based on Brazil (Penteado and Rosado, 2016).

Table 4
Methods and indicators for assessing the environmental impacts of CDWM. Environmental performance assessment indicators in CDWM studies (Sustainability based thinking).

Authors	(Gomes et al., 2008)	(Manowong, 2012)	(Marrero et al., 2017)	(Klang et al., 2003)	(Roussat et al., 2009)	(Merino et al., 2010)	(Tam et al., 2010)
Method	Multiple criteria decision making	Structural equation modelling	work breakdown system	Original model	Original model	Original model	Original model
Indicators	CO2 emissions	Waste generation Air quality Water quality Resource consumption Land degradation Energy consumption	Energy Waste Land Water Food Consumption	Energy consumption avoided Carbon dioxide equivalents saved Potential acidification avoided	Energy resource conservation Material resource conservation	Natural resource Air quality Water quality Energy	Reducing the need for new landfills Saving natural materials

3.3.2. Scenarios setting

Scenario analysis is employed to determine optimal CDWM scenarios. There are two categories to set up scenario in previous C&D waste LCA studies, which are: (a) making the comparison among current practice situation, targets in CDWM plan, ideal prospects (i.e., Maximum Recycling, Maximum Energy Recovery) and worse case (i.e., Landfill) (Bohne et al., 2008; Wu et al., 2015; Ortiz et al., 2010; Chau et al., 2017); and (b) making the comparison among different treatment facility/system. For instance, Mercante et al. (2012) compared the performance between small-scale mixed C&D waste sorting facility and larger-scale C&D waste recycling centre. The similar scenario setting was adopted in other studies (Dahlbo et al., 2015; Penteado and Rosado, 2016). Apart from this, Wang et al. (2018) compared the factory C&D waste recycling with the mobile on-site C&D waste recycling. Scenario analysis helps to determine the more suitable CDWM method and to make strategical recommendations to the decision makers for enhancing CDWM performance as a whole.

3.3.3. Inventory analysis

The most demanding task in performing an LCA is data collection. Although much secondary data is available in literature or database like *ecoinvent*, it is usually found that at least a few processes or materials are unavailable (Goedkoop et al., 2008). Therefore, a systematical data collection plan is helpful to establish the inventory (Dahlbo et al., 2015; Penteado and Rosado, 2016). Previous studies have developed some strategies to collect data. Regarding the foreground data used to create the modelling system, it is normally collected from specific companies via interview or questionnaires. Since these data may involve confidentiality issues and terminology issues, the willingness to provide such data sometimes depends on the relationship between the researchers and data owners. For instance, to collect deserved data, Penteado and Rosado (2016) not only conducted sites visit on recycling projects but also organised regular meetings with technicians from CDWM Departments of the Municipality. In terms of the background data for the production of generic materials, energy, transport, and waste management, it is usually available in databases or can be found in the literature. In most cases, an extensive literature review was essential to fulfil the missing data in the database (Dahlbo et al., 2015). The most welcomed data sources for the background data in C&D waste LCA studies is the *ecoinvent* database, which has been adopted by several studies (Bohne et al., 2008; Mercante et al., 2012; Ortiz et al., 2010; Wu et al., 2015; Wang et al., 2018).

3.3.4. Impact assessment

According to ISO 14040/44, life cycle impact assessment is designed to understand and evaluate the magnitude and significance of potential environmental impacts of the system. It usually contents essential elements (i.e., classification and characterization) and optional elements (i.e., normalization, ranking, grouping, and weighting) (ISO 14040/44). Previous C&D waste LCA studies usually select one well-developed impact assessment method or a refined method, rather than create impact assessment methodologies. For instance, Bohne et al. (2008) chose the EcoIndicator 99 method because it is a single value indicator and easy to communicate the results to decision makers. Wang et al. (2018) adopted the IPCC 2013 GWP 100a V1.01 to calculate the carbon emissions of raw material substitute in their study. Distinguished from most studies, Butera et al. (2015) employed EASETECH, a model for LCA of waste and energy systems developed by the Technical University of Denmark. In order to suit the characterizations of C&D waste, Ortiz et al. (2010) added other eco-efficiency indicators, such as resources use, renewable energy, non-renewable energy and overall water use, into their refined method, based on the CML 2 baseline 2000 methodology (CML, 2001) for the evaluation of the environmental profile.

In contrast, Penteado and Rosado (2016) excluded the possible leachate emissions to the soil and water, the impact categories of human toxicity, aquatic and terrestrial ecotoxicity from the CML 2

Table 5
Indicators for economic performance assessment in CDWM studies.

Authors	(Klang et al., 2003)	(Begum et al., 2006)	(Duran et al., 2006)	(Bohne et al., 2008)	(Gomes et al., 2008)
Method	Original model	Original model	Original model	LCA	Multiple criteria decision making
indicators source	Literature review, questionnaires	Case study	Postal survey and telephone survey	N/A	Multicriteria Decision Aiding Hybrid Algorithm (THOR)
Indicators	Energy costs	Benefit	Transportation cost	Transfer costs	Investments
	Labour cost	Purchasing cost savings by reusing and recycling	Landfill charge	Taxes	Operational costs
	Transportation cost	Revenue from selling of scrap waste materials	Recycling charge		Disposal/treatment costs
	Retail price	Waste transportation cost saving	Extra recycling charge		
		Cost savings from landfill charge	Primary aggregates prices		
		Cost	Recycled aggregate cost (detailed)		
		Collection and separation costs	Extra recycling cost		
		Equipment purchasing cost	Imposition of taxes - landfills		
		Storage cost	Subsidy - recycling		
		Transportation Costs			
Authors	(Shen et al., 2009)	(Tam et al., 2010)	(Zhao et al., 2010)	(Yuan et al., 2011)	(Zhao et al., 2011)
Method	Original model	Original model	Original model	Original model	SD/Original model
indicators source	case study	Questionnaire survey and structured interviews	Case study	Secondary data	Secondary data
Indicators	landfill charges	Reducing project cost by using recycled materials	Capital costs	Emdollar value	Profit
	transportation cost	saving transportation cost	Construction works	Energy yield ratio	unit recycling cost
	Placing cost		Cost for equipment		extra revenue from location advantage
			Land costs		
			Opportunity costs		
			Operational costs		
			Labour cost		
			Energy cost		
			Disposal cost		
Authors	(Manowong, 2012)	(Srour et al., 2013)	(Yuan, 2013)	(Tam et al., 2014)	(Ding et al., 2016a,b)
Method	Structural equation modelling	Original model	Original model	SD/Original model	SD
indicators source	Questionnaire	Case study	Literature review	Secondary data	Secondary data and interview
Indicators	Economic sustainability	Economic indicators	Economic performance	Increasing GDP	Cost of waste collection
	Economic incentives	Daily labour rates	Cost of waste collection, sorting and separation	illegal dumping cost	On-site sorting cost
	cost effectiveness	cost of site clearing, levelling and filling	Cost of waste reuse	transportation cost	Cost of illegal dumping disposal
	expenditures	cost of border fence	Cost of waste recycling	landfill charge	
	revenues	cost of pre-fabricated site offices	Cost of waste transportation	saving cost	
	recycling interests	annual increase of operating costs	Cost of disposing waste at landfills	recycling cost	
		Maintenance and insurance costs	Penalty paid due to illegal dumping of waste	landfill cost	
			Revenue from selling waste materials		
			Saving in waste transportation		
			Saving in cost for disposing of waste at landfills		

baseline 2001 methodology (CML, 2001). Since some studies only focused on a single issue, like energy saving (Chau et al., 2017) or carbon emissions (Wu et al., 2015), they used so-called single issue methods, which is relatively robust and easy to use. However, it is noticed that single-issue methods are not in compliance with ISO 14044 as this standard requires a thoughtful assessment of all relevant impact categories (Goedkoop et al., 2008). It is not easy to determine which method should be optimal, as these methods are developed by different research teams around the globe.

4. Critical indicators for assessing CDWM performance

Previous studies mainly focus on the environmental, economic and social performance of CDWM. Some studies may choose one or two of the performance categories while some others conduct a comprehensive assessment covering all three aspects. Table 1 lists the primary studies on CDWM performance assessment. It shows that compared to environmental and economic aspects, social aspect has attracted less attention, though the social impacts have been highlighted by some studies (Chung et al., 2003; Klang et al., 2003; Yuan, 2012, ; Manowong et al., 2012).

4.1. Indicators for environmental performance assessment

Although the goals for assessing the environmental performance of CDWM can be similar, the selection of methods and indicators varies among different studies, which is discussed as follows:

4.1.1. Using a well-developed method for environmental impact assessment
In terms of LCA studies, most studies did not create their impact assessment methodologies; instead, they chose to select a sophisticated method for assessment (Bohne et al., 2008; Butera et al., 2015; Penteado and Rosado, 2016). Regarding the LCA, such impact assessment methods can be found in software such as *SimaPro*. These methods are developed by various research teams and subsequently used around the globe, though there has been no consensus yet on the "best

Table 6
Indicators for social performance assessment in CDWM studies.

Authors	(Chung and Lo, 2003)	(Klang et al., 2003)	(Manowong, 2012)		(Yuan, 2012)	(Yuan, 2013)
Method	Original model	Original model	Structural equation modelling		SD	Original model
indicators source	Review	Literature, questionnaires, documents	N/A	Waste handling	Case study/literature review	Literature review
Indicators	Social acceptability and equity	Worker's evaluation of physical working environment	Health impact	Safety training	Illegal construction waste dumping on society image	Practitioners' awareness to manage waste
		Worker's estimates of socio - psychological work environment	Accident prevention	Gender equality	Physical working environment	Provision of job opportunities
		Percentage of workers that after the project would consider working within the field	Casualty prevention	Gender equality	Job opportunities	Physical working condition
		Degree of employment after finishing project	Health condition	Gender respect	Operative safety	Impacts on long-term health
			Exposure to risks	Workplace diversity	Practitioners long-term health	Safety of operatives in conducting waste management
			Mental health	Fairness		Public satisfaction about C&D waste management
			Health policy & practice	Stakeholder participation		Public appeal for regulating illegal waste dumping
			Health awareness	Susceptibility		Impacts of illegal waste dumping on social image

method." As a result, most LCA practitioners seem to choose a method by popularity, or worse, adopting a default method integrated with the software used. Besides, instead of selecting one general method, some experts may select individual impact categories such as carbon emission and energy consumption (Chau et al., 2017; Wang et al., 2018).

4.1.2. Refining a method for environmental impact assessment

Although impact assessment methods become very extensive and include more and more substances, they still do not cover all elements essential for comprehensive environmental assessment. This can be a methodological issue, because some methods, for example, do not include raw materials as impact category. Therefore, some studies refined the impact assessment method according to their research need. For instance, Ortiz et al. (2010) have to add four additional indicators including resources use, renewable energy, non-renewable energy and overall waste use in their model based on the CML 2 model.

4.1.3. Creating an original model involving performance assessment indicators

Compared to the LCA, SD studies have not developed comprehensive environmental impacts assessment methods. Those studies usually developed original models with performance assessment indicators derived from literature review, case study, or interview (Marzouk and Azab, 2014; Ye et al., 2012; Yuan, 2013; Ding et al., 2016a,b). Besides, there are some other approaches adopted in assessing environmental performance (Marrero et al., 2017). These indicators mainly consider the environmental components concerning air, water, raw material resource, energy, land, and noise. The choice of the indicators is mostly dependent on the goal and scope of studies (Tables 2,3,4).

4.2. Indicators for economic performance assessment

Economic aspect also attracted significant attention in previous studies. The economic performance assessment of C&D waste mainly focus on the cost aspect, and only a few studies take the benefit or revenue into considerations (Begum et al., 2006; Manowong, 2012; Zhao et al., 2011). The calculations of C&D waste handling costs were considered differently among different studies. For instance, some studies divide the cost according to the procedure of processing C&D waste, such as collection, transportation, landfilling, recycling and so on (Begum et al., 2006; Duran et al., 2006; Tam et al., 2014); some studies consider the cost of input resources, such as labour, energy, equipment, land and so on (Klang et al., 2003; Srour et al., 2013; Zhao et al., 2010); while some studies use more abstractive indicators such as investments, operational costs, treatment/disposal costs; taxes, and subsidies (Bohne et al., 2008; Gomes et al., 2008; Zhao et al., 2011). Table 5 summarises the methods and indicators used for assessing the economic performance of CDWM.

It is found that unlike the environmental performance assessment, there are not many well-developed methods for economic performance assessment. Although the possibility of adding economic issues to the LCA methodology has been discussed among studies such as Life Cycle Cost Assessment, often these debates are confused and not productive (Goedkoop et al., 2008). There are numerous difficulties in accurately assessing the economic performance of CDWM. Firstly, the vital cost factors such as investment, research, overheads, and marketing are usually not modelled or at least underrepresented in a well-developed model such as the LCA model. Secondly, previous models do not have a time perspective, which makes it challenging to model interest or discount rates. Also, the precision requirements for cost and revenue calculations are high. An error in the computation of a sales margin of a few percent can be disastrous for a company. Many companies, therefore, input heavy human resources to keep track of market prices, exchange rates, and sales margins. It is not realistic to assume that an LCA expert can make an improvement on this. The last but not least, the economic data usually are confidential commercial information for

The framework of assessing C&D waste management performance		Sustainability based thinking	Systems thinking	Life cycle thinking
System boundary	Particular activities	Chung, S. S. 2003; Shen, L. Y.2009; Zhao W 2010; Yuan, F.2011;Dahlbo, H.2015; Gomes, C. F. S.2008; Klang, A. 2003; Begum, R. A.2006; Duran, X.2006; da Rocha, C. G. 2009; Marino, M. D.2010; Tam.V.W.Y 2010; Saez, P. V.2013	Zhao, W.2011; Ye, G.2012; Yuan, H. P.2012; Tam, V. W. Y.2014; Ding, Z. K.2016	
	Entile life cycle			Bohne, R. A. 2008; Mercante, I. T.2012; Simion, I. M.2013; Stefania, B, 2015; Kucukvar, M.2016; Penteado, C. S. G.2016; Zambrana-Vasquez, D.2016; Ortiz, O.2010; Chau, C. K. 2017
Research scale	Project level	Lu, M.2009		(Ortiz et al., 2010); (Chau et al., 2017) (J. Wang et al., 2018)
	City level	Chung, S. S. 2003; Shen, L. Y.2009; Zhao W 2010; Yuan, F.2011	Zhao, W.2011; Ye, G.2012; Yuan, H. P.2012; Tam, V. W. Y.2014; Ding, Z. K.2016	(Bohne et al., 2008); (Wu et al., 2015);
	National level	Dahlbo, H.2015; Gomes, C. F. S.2008; Klang, A. 2003; Begum, R. A.2006; Duran, X.2006; da Rocha, C. G. 2009; Marino, M. D.2010; Tam.V.W.Y 2010; Saez, P. V.2013	Marzouk, M.2014	(Mercante et al., 2012); (Penteado & Rosado, 2016)
Performance aspects	Environmental	Dahlbo, H.2015; Gomes, C. F. S.2008;Chung, S. S. 2003; Klang, A. 2003; Roussat, N.2009; Marino, M. D.2010; Tam.V.W.Y 2010; Yuan, F.2011; Yuan, H P.2013	Ye, G.2012; Marzouk, M.2014; Tam, V. W. Y.2014; Manowong, E.2012; Mamiro, M.2017	Bohne, R. A. 2008; Mercante, I. T.2012; Simion, I. M.2013; Stefania, B, 2015; Kucukvar, M.2016; Penteado, C. S. G.2016; Zambrana-Vasquez, D.2016; Ortiz, O.2010; Chau, C. K. 2017
	Economic	Lu, M.2009; Dahlbo, H.2015; Gomes, C. F. S.2008; Chung, S. S. 2003; Klang, A. 2003; Begum, R. A.2006; Duran, X.2006; da Rocha, C. G. 2009; Shen, L. Y.2009; Zhao W 2010; Srour, I. M.2014; Yuan, H. P.2013	Zhao, W.2011; Marzouk, M.2014; Tam, V. W. Y.2014; Manowong, E.2012, Ding, Z. K.2016	Bohne, R. A. 2008; Kucukvar, M.2016
	Social	Chung, S. S. 2003; Klang, A. 2003; Yuan, H. P.2013	Yuan, H. P.2012; Manowong, E.2012	

Fig. 4. The framework of assessing CDWM performance.

companies, making it difficult to obtain such data from public sources or through interviewing CDWM practicians.

4.3. *Social performance assessment indicators*

Compared to environmental and economic impact assessment, social impact assessment has attracted less attention. Typically, social impact assessment relates closely to different stakeholder groups throughout the life cycle of construction and demolition activities, including employees, consumers, and local communities. Social impact assessment often concerns issues like wages, health and safety, and access to education. The barriers to conducting adequate social impact assessment lie in that the issues at stake are wide-ranging and often difficult to quantify in a meaningful way (Goedkoop et al., 2008).

The selection of social performance assessment indicators shows significant differences among studies between stakeholder-based and impact category-based. For instance, Klang et al. (2003) focused on the worker's point of view, while some studies consider the public apart from the employees (Yuan, 2012 and 2013). From the impact category-based structure, Manowong (2012) selected a wide-ranging indicator such as employees' health, exposure to risks, safety, gender equality, workplace diversity, fairness and so on; on the other hand, Chung and Lo (2003) selected an abstract indicator namely social acceptability and equity to assess the social performance of CDWM. Table 6 summarises the methods and indicators for assessing the social performance of CDWM.

Since there are wide-ranging aspects in considering the social issues, it is suggested that the first step is the identification of the most relevant aspects. Apart from the methods and indicators in previous studies, there are also some references available for conducting a social impacts assessment (Goedkoop et al., 2008), such as the UNEP SETAC (Benoît-Norris et al., 2011), the Global Reporting Initiative (GRI), the United Nations Global Compact (UNGC), and the ISO 26000 for social responsibility.

5. A framework for CDWM performance assessment

5.1. *Framework for performance assessment*

Although significant achievements have been made to assess CDWM in recent years, there is a lack of a general framework to cover the critical aspects in assessing CDWM performance. With such a framework, researchers can quickly understand the prior development of performance assessment methods and indicators in the field; practitioners and policymakers can gain a comprehensive understanding of the significance and complexity of environmental, economic and social impacts of CDWM, which is helpful to improve the practices. Based on an in-depth analysis of the samples, the study proposes a framework for

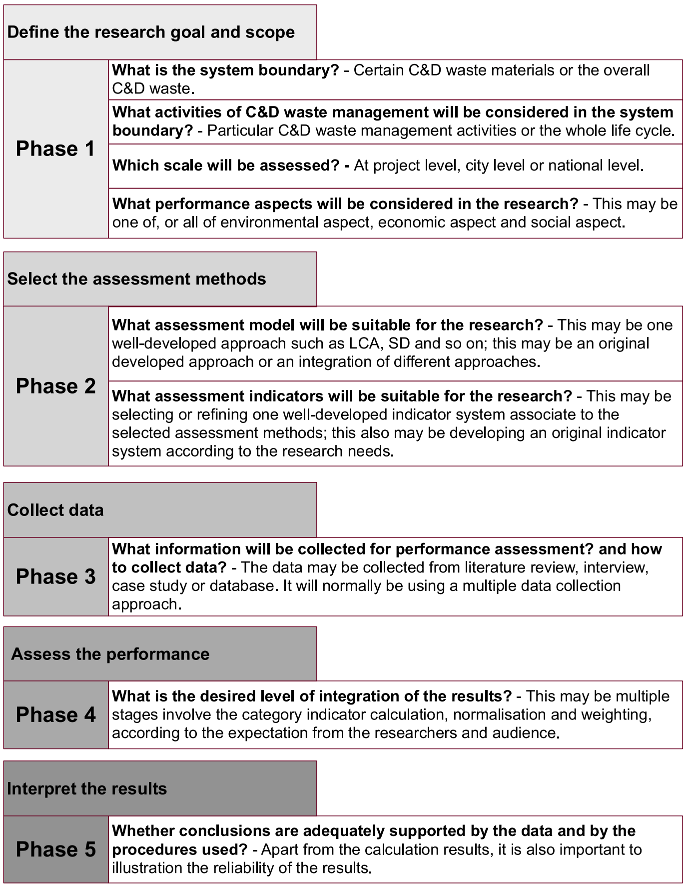


Fig. 5. A five-step procedure for assessing CDWM performance.

CDWM performance assessment research in terms of system boundary, research scale and performance aspects (Shown in Fig. 4).

In terms of the research objectives, previous life cycle thinking based studies focus more on the entire lifecycle of CDWM, from waste generation to its final disposal (Bohne et al., 2008; Chau et al., 2017; Kucukvar et al., 2016; Mercante et al., 2012; Ortiz et al., 2010; Penteado and Rosado, 2016; Simion et al., 2013; Wang et al., 2018; Wu et al., 2015). System thinking based studies focus mainly on the development of CDWM systems containing a series of waste management activates such as reuse, recycling and landfilling (Zhao et al., 2011; Ye et al., 2012; Yuan, 2012; Marzouk and Azab, 2014; Tam et al., 2014; Ding et al., 2016a,b). Differently, the sustainability based studies show a priority on the assessment of particular CDWM activities such as recycling and landfilling (Kucukvar et al., 2016; Marrero et al., 2017; Wang et al., 2004; Stenis, 2005; Roussat et al., 2009; Srour et al., 2013; Butera et al., 2015; Ding et al., 2016a,b; Dejkovski, 2016; Yuan, 2012).

Considering the research scale, studies from different research streams show very different priorities. The majority of system thinking based studies focus primarily on CDWM issues at a city level (Zhao et al., 2011; Ye et al., 2012; Yuan, 2012; Ding et al., 2016a,b; Tam et al., 2014); while the sustainability based studies show their favours on issues at a national level more than at the city or project level (Begum et al., 2006; Duran et al., 2006; Tam, 2008). The distribution of life cycle thinking based studies is somehow equally distributed among different levels.

It can be observed that not many studies have been conducted on assessing the social performance of CDWM (Manowong, 2012; Yuan, 2012). The life cycle thinking studies mostly concentrate on environmental issues of CDWM (Butera et al., 2015; Kucukvar et al., 2016). Given the nature priority of current LCA method, there is no attempt to consider the social issues into the life cycle thinking based studies when assessing CDWM performance. The distributions of studies on the performance aspects are identical between the sustainability-based research stream and system thinking based stream. They pay much attention to the environmental and economic aspects of CDWM.

5.2. Procedure for assessing CDWM performance

An analysis of the methodologies adopted in the selected CDWM performance assessment studies came out some common research procedures. By integrating and streamlining the critical research processes extracted from the previous studies of the three themes, i.e., sustainability based thinking, life cycle thinking, and systems thinking, we propose a five-step procedure for assessing CDWM performance (Fig. 5).

Generally, the first step is to define the research goal and scope, which is critical in determining the selection of methods and designing the whole research. At this stage, four questions should be considered:

- what is the system boundary? Considering certain types of C&D waste materials or the overall C&D waste.
- What activities (scenarios) of CDWM will be considered? Concentrating on particular C&D waste management activities or assessing the whole life cycle.
- Which scale will be assessed? Scoping the study at project level, city level or national level.
- And what performance aspects will be involved? e.g., either focusing on one of the three dimensions of performance (i.e., environmental, economic, and social) or covering all of them. Previously the goals and scopes are defined from various elements, which may be an overall CDWM system at the project level, city level or national level (Bohne et al., 2008); or maybe the treatment of one or several C&D waste materials (Butera et al., 2015).

The second step is to select the assessment methods. It needs to consider two main aspects:

- what assessment model will be suitable? This may be resolved by selecting a well-developed approach such as LCA and SD (Bohne et al., 2008; Chau et al., 2017; Kucukvar et al., 2016; Mercante et al., 2012; Ortiz et al., 2010; Penteado and Rosado, 2016; Simion et al., 2013; Wang et al., 2018; Wu et al., 2015; Ding, et al., 2016; Marzouk and Azab, 2014; Yuan, 2012); or considering an originally developed approach or an integration of different approaches (Ajayi et al., 2015).
- The second question is what assessment indicators will be suitable. The study may select or refine a well-developed indicator system associated with the selected assessment methods (Ortiz et al., 2010); or develop an original indicator system according to the research needs (Marrero et al., 2017). The selection of criteria is frequently achieved through a literature survey.

The third step is to collect data, in which significant efforts should be paid to figure out: what information will be collected for assessment; and how to collect data. The data may be collected from the literature review, interview and case study, or through visiting databases. Generally, multiple data resources would be adopted in such studies (Dahlbo et al., 2015; Penteado and Rosado, 2016).

The fourth step is to assess the performance. It is worth considering what the desired level of integration of the results is, and this will affect the accuracy requirement and presentation forms of the results. There are multiple stages involving the category indicator calculation, normalisation, and weighting, according to the expectation of the researchers and audience (ISO 14040/44). Most studies would provide quantitative results while sometimes studies would result in qualitative recommendations for policy development (Saez et al., 2013; Yuan, 2013).

The final step is to interpret the results. Typically, this is associated with the scenario analysis of results, which is critical for findings' implications. It is also important to consider whether conclusions are adequately supported by the data and by the procedures used. Besides the calculation results, it is crucial to illustrate the reliability of the results in such studies. For instance, when adopting an LCA method, the result interpretation includes uncertainty analysis, sensitivity analysis, contribution analysis and inventory analysis (ISO 14040/44).

6. Conclusions

The effective approach to evaluate CDWM performance has become a critical issue. This study provides a review of literature presenting performance assessment methods for CDWM. By analysing the studies in terms of research methods, data collection methods, and critical indicators employed, we assessed the adoptability of developed methods regarding theoretical development and limitations. In particular, the study found that:

- Significant efforts have been made for developing models to assess CDWM performance. Three main research streams regarding CDWM performance assessment: sustainability-based methods, system thinking-based methods, and life cycle thinking-based methods have been developed in prior studies.
- A considerable percentage of previous studies used well-developed methods such as LCA and SD for CDWM performance assessment.
- Deferent research streams have different research priorities; for instance, the majority of studies adopted LCA mainly concentrate on the environmental aspect due to the nature of the method. SD, much differently, has a broader targeting on covering various aspects including economic, environmental and social.
- It is shown that compared to environmental and economic aspects, the social aspect has attracted less attention, though the social aspect is critical for understanding the overall impact of CDWM.
- Significant studies indicated that the economic feasibility of CDWM strategies would depend on various factors, such as the economics of scale, the methods of recycling, cost of landfilling, transportation distance and so on.
- Although some scholars provide recommendations from various aspects to enhance the economic viability of C&D waste recycling, to be concerned that, the effective of adopting policy to improve the economic performance of CDWM can be hardly validated.
- The management effectiveness-focused research is mainly targeting the development of the concept and the development of indicators to assess the management effectiveness at different levels. Hence, more efforts are called to expand the research of the effectiveness of CDWM in the future.
- Although there are a number of studies employing SD to assess CDWM performance, the validation of SD model is controversial among many discussions due to the nature of the methodology.
- In terms of data collection, different research streams adopted different methods. For instance, sustainability-based studies mainly use interview, questionnaires or case study to validate the adoptability of the models; System dynamics particularly the valuation of variables based on multiple methods, including theoretical assumption, experts' estimation, and secondary data; In the LCA studies regarding the foreground data used to create the modelling system, it is normally collected from specific companies via interview or questionnaires. The most welcomed data sources for the background data in C&D waste LCA studies is the *ecoinvent* database.

Although significant achievements have been made to assess CDWM performance in recent years, there lacks a general framework to cover the critical aspects in the performance assessment of CDWM. Through the study, we propose a framework capable of integrating the methodologies adopted in existing studies, which concerns the system boundary, research scale, and performance assessment aspects. With this proposed overarching framework, researchers can quickly understand the prior development of performance assessment methods and indicators in the field.

An analysis of the methodologies adopted in selected published studies of CDWM performance assessment found some common research procedures. By integrating and streamlining the critical research processes extracted from the previous studies, the study provides a useful and generic procedure for assessing CDWM performance. It includes: (1) defining the research goal and scope; (2) selecting the assessment methods; (3) collecting data; (4) assessing the performance; and (5) interpreting the results. The expertise on current performance assessment practices in CDWM and the proposed framework supply the basis for the development of sound CDWM methods and makes it possible for better understand for environmental, economic, and social performance for CDWM.

Acknowledgements

The authors wish to acknowledge the financial support from the National Natural Science Foundation of China (Grant number: 71573216) and the Shenzhen Science and Technology Plan (No. JCYJ20160520173631894). The authors also would like to appreciate Mrs. Gillian Armstrong for her language editing of the manuscript.

Appendix A

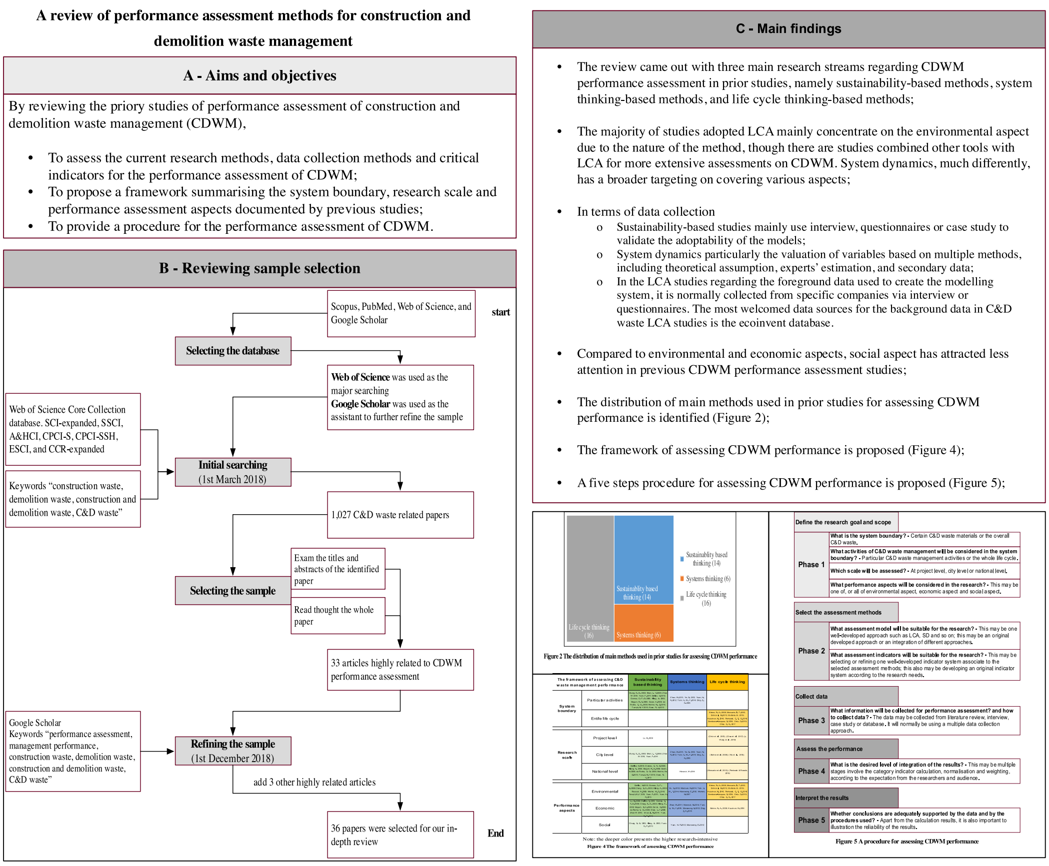


Fig. A1. Graphical abstract.

Table A1
list of the reviewed paper in CDWM studies.

	Author	Region	Paper tittle	Journal
1	(Chung and Lo, 2003)	Hong Kong	Evaluating sustainability in waste management: the case of construction and demolition, chemical and clinical wastes in Hong Kong	Resources Conservation and Recycling
2	(Klang et al., 2003)	Norway and Sweden	Sustainable management of demolition waste - an integrated model for the evaluation of environmental, economic and social aspects	Resources Conservation and Recycling
3	(Begum et al., 2006)	Malaysia	A benefit-cost analysis on the economic feasibility of construction waste minimization: The case of Malaysia	Resources Conservation and Recycling
4	(Duran et al., 2006)	Ireland	A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland	Resources Conservation and Recycling
5	(Bohne et al., 2008)	Norway	Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level	Journal of Industrial Ecology
6	(Gomes et al., 2008)	Brazil	Multicriteria decision making applied to waste recycling in Brazil	Omega-International Journal of Management Science
7	(da Rocha and Sattler, 2009)	Brazil	A discussion on the reuse of building components in Brazil: An analysis of major social, economic and legal factors	Resources Conservation and Recycling
8	(Lu et al., 2009)	Hong Kong	Simulation Approach to Evaluating Cost Efficiency of Selective Demolition Practices: Case of Hong Kong's Kai Tak Airport Demolition	Journal of Construction Engineering and Management
9	(Roussat et al., 2009)	N/A	Indicators to assess the recovery of natural resources contained in demolition waste	Waste Management & Research
10	(Shen et al., 2009)	Hong Kong	Benefit analysis on replacing in situ concreting with precast slabs for temporary construction works in pursuing sustainable construction practice	Resources Conservation and Recycling
11	(Merino et al., 2010)	Spain	Sustainable construction: construction and demolition waste reconsidered	Waste Management & Research
12	(Ortiz et al., 2010)	Spain	Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain	Waste Management
13	(Tam et al., 2010)	Australia, Hong Kong, Japan	Cross-cultural comparison of concrete recycling decision-making and implementation in construction industry	Waste Management
14	(Zhao et al., 2010)	China/Chongqing	Evaluation of the economic feasibility for the recycling of construction and demolition waste in China-The case of Chongqing	Resources Conservation and Recycling
15	(Yuan et al., 2011)	China/Shanghai	Emergy analysis of the recycling options for construction and demolition waste	Waste Management
16	(Zhao et al., 2011)	China/Chongqing	A system dynamics model for evaluating the alternative of type in construction and demolition waste recycling centre - The case of Chongqing, China	Resources Conservation and Recycling
17	(Manowong, 2012)	Thailand	Investigating factors influencing construction waste management efforts in developing countries: an experience from Thailand	Waste Management & Research
18	(Mercante et al., 2012)	Spain	Life cycle assessment of construction and demolition waste management systems: a Spanish case study	International Journal of Life Cycle Assessment
19	(Ye et al., 2012)	China/Shenzhen	Simulating effects of management measures on the improvement of the environmental performance of construction waste management	Resources Conservation and Recycling
20	(Yuan, 2012)	China/Shenzhen	A model for evaluating the social performance of construction waste management	Waste Management
21	(Simion et al., 2013)	Italy	Ecological footprint applied in the assessment of construction and demolition waste integrated management	Environmental Engineering and Management Journal
22	(Srour et al., 2013)	Lebanon	Pilot-based assessment of the economics of recycling construction demolition waste	Waste Management & Research
23	(Yuan, 2013)	N/A	Key indicators for assessing the effectiveness of waste management in construction projects	Ecological Indicators
24	(Marzouk and Azab, 2014)	Egypt	Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics	Resources Conservation and Recycling
25	(Tam et al., 2014)	China/Shenzhen	System dynamic modelling on construction waste management in Shenzhen, China	Waste Management & Research
26	(Butera et al., 2015)	Denmark	Life cycle assessment of construction and demolition waste management	Waste Management
27	(Dahlbo et al., 2015)	Finland	Construction and demolition waste management - a holistic evaluation of environmental performance	Journal of Cleaner Production
28	(Dejkovski, 2016)	Australia	Assessing the environmental performance of construction materials testing using EMS: An Australian study	Waste Management
39	(Ding et al., 2016a,b)	China/Shenzhen	An agent based environmental impact assessment of building demolition waste management: Conventional versus green management	Journal of Cleaner Production
30	(Ding et al., 2016a,b)	China/Shenzhen	A system dynamics-based environmental performance simulation of construction waste reduction management in China	Waste Management
31	(Kucukvar et al., 2016)	USA	Life Cycle Assessment and Optimization-Based Decision Analysis of Construction Waste Recycling for a LEED-Certified University Building	Sustainability
32	(Penteado and Rosado, 2016)	Brazil	Comparison of scenarios for the integrated management of construction and demolition waste by life cycle assessment: A case study in Brazil	Waste Management & Research
33	(Zambrana-Vasquez et al., 2016)	Spain	Analysis of the environmental performance of life-cycle building waste management strategies in tertiary buildings	Journal of Cleaner Production
34	(Chau et al., 2017)	Hong Kong	Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building	Applied Energy
35	(Marrero et al., 2017)	Spain	Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land	Resources Conservation and Recycling
36	(Wang et al., 2018)	China/Shenzhen	Combining Life Cycle Assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study	Journal of Cleaner Production

References

Ajayi, S.O., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A., Owolabi, H.A., Kadiri, K.O., 2015. Waste effectiveness of the construction industry: understanding the impediments and requisites for improvements. Resour. Conserv. Recycl. 102, 101–112. https://doi.org/10.1016/j.resconrec.2015.06.001.

Begum, R.A., Siwar, C., Pereira, J.J., Jaafar, A.H., 2006. A benefit-cost analysis on the economic feasibility of construction waste minimisation: the case of Malaysia. Resour. Conserv. Recycl. 48 (1), 86–98. https://doi.org/10.1016/j.resconrec.2006.01.004.

Benoît-Norris, C., Vickery-Niederman, G., Valdivia, S., Franze, J., Traverso, M., Ciroth, A., Mazijn, B., 2011. Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. Int. J. Life Cycle Assess. 16 (7), 682–690.

Bohne, R.A., Brattebo, H., Bergsdal, H., 2008. Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level. J. Ind. Ecol. 12 (1), 52–68. https://doi.org/10.1111/j.1530-9290.2008.00013.x.

Butera, S., Christensen, T.H., Astrup, T.F., 2015. Life cycle assessment of construction and demolition waste management. Waste Manag. 44, 196–205. https://doi.org/10.1016/j.wasman.2015.07.011.

Chau, C.K., Xu, J.M., Leung, T.M., Ng, W.Y., 2017. Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building. Appl. Energy 185, 1595–1603. https://doi.org/10.1016/j.apenergy.2016.01.019.

Chung, S.S., Lo, C.W.H., 2003. Evaluating sustainability in waste management: the case of construction and demolition, chemical and clinical wastes in Hong Kong. Resour. Conserv. Recycl. 37 (2), 119–145. https://doi.org/10.1016/s0921-3449(02)00075-7.

da Rocha, C.G., Sattler, M.A., 2009. A discussion on the reuse of building components in Brazil: an analysis of major social, economical and legal factors. Resour. Conserv. Recycl. 54 (2), 104–112. https://doi.org/10.1016/j.resconrec.2009.07.004.

Dahlbo, H., Bacher, J., Lahtinen, K., Jouttijarvi, T., Suoheimo, P., Mattila, T., et al., 2015. Construction and demolition waste management - a holistic evaluation of environmental performance. J. Clean. Prod. 107, 333–341. https://doi.org/10.1016/j.jclepro.2015.02.073.

Dejkovski, N., 2016. Assessing the environmental performance of construction materials testing using EMS: an Australian study. Waste Manag. 56, 359–366. https://doi.org/10.1016/j.wasman.2016.07.016.

Ding, Z.K., Wang, Y.F., Zou, P.X.W., 2016a. An agent based environmental impact assessment of building demolition waste management: conventional versus green management. J. Clean. Prod. 133, 1136–1153. https://doi.org/10.1016/j.jclepro.2016.06.054.

Ding, Z.K., Yi, G.Z., Tam, V.W.Y., Huang, T.Y., 2016b. A system dynamics-based environmental performance simulation of construction waste reduction management in China. Waste Manag. 51, 130–141. https://doi.org/10.1016/j.wasman.2016.03.001.

Duran, X., Lenihan, H., O'Regan, B., 2006. A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland. Resour. Conserv. Recycl. 46 (3), 302–320. https://doi.org/10.1016/j.resconrec.2005.08.003.

Goedkoop, M., De Schryver, A., Oele, M., Durksz, S., de Roest, D., 2008. Introduction to LCA With SimaPro 7. PRé Consultants, The Netherlands.

Gomes, C.F.S., Nunes, K.R.A., Xavier, L.H., Cardoso, R., Valle, R., 2008. Multicriteria decision making applied to waste recycling in Brazil. Omega-Int. J. Manag. Sci. 36 (3), 395–404. https://doi.org/10.1016/j.omega.2006.07.009.

Jung, J.S., Song, S.H., Jun, M.H., Park, S.S., 2015. A comparison of economic feasibility and emission of carbon dioxide for two recycling processes. Ksce J. Civ. Eng. 19 (5), 1248–1255. https://doi.org/10.1007/s12205-015-0708-2.

Klang, A., Vikman, P.A., Brattebo, H., 2003. Sustainable management of demolition waste - an integrated model for the evaluation of environmental, economic and social aspects. Resour. Conserv. Recycl. 38 (4), 317–334. https://doi.org/10.1016/s0921-3449(02)00167-2.

Kucukvar, M., Egilmez, G., Tatari, O., 2016. Life cycle assessment and optimization-based decision analysis of construction waste recycling for a LEED-Certified university building. Sustainability 8 (1), 13. https://doi.org/10.3390/su8010089.

Lu, M., Lau, S.C., Poon, C.S., 2009. Simulation approach to evaluating cost efficiency of selective demolition practices: case of Hong Kong's Kai Tak Airport Demolition. J. Constr. Eng. Manag. 135 (6), 448–457. https://doi.org/10.1061/(asce)0733-9364(2009)135:6(448).

Manowong, E., 2012. Investigating factors influencing construction waste management efforts in developing countries: an experience from Thailand. Waste Manag. Res. 30 (1), 56–71. https://doi.org/10.1177/0734242x10387012.

Marrero, M., Puerto, M., Rivero-Camacho, C., Freire-Guerrero, A., Solis-Guzman, J., 2017. Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land. Resour. Conserv. Recycl. 117, 160–174. https://doi.org/10.1016/j.resconrec.2016.10.020.

Marzouk, M., Azab, S., 2014. Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. Resour. Conserv. Recycl. 82, 41–49. https://doi.org/10.1016/j.resconrec.2013.10.015.

McDougall, F.R., White, P.R., Franke, M., Hindle, P., 2008. Integrated Solid Waste Management: a Life Cycle Inventory. John Wiley & Sons.

Mercante, I.T., Bovea, M.D., Ibanez-Fores, V., Arena, A.P., 2012. Life cycle assessment of construction and demolition waste management systems: a Spanish case study. Int. J. Life Cycle Assess. 17 (2), 232–241. https://doi.org/10.1007/s11367-011-0350-2.

Merino, M.D., Gracia, P.I., Azevedo, I.S.W., 2010. Sustainable construction: construction and demolition waste reconsidered. Waste Manag. Res. 28 (2), 118–129. https://doi.org/10.1177/0734242x09103841.

Ortiz, O., Pasqualino, J.C., Castells, F., 2010. Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. Waste Manag. 30 (4), 646–654. https://doi.org/10.1016/j.wasman.2009.11.013.

Penteado, C.S.G., Rosado, L.P., 2016. Comparison of scenarios for the integrated management of construction and demolition waste by life cycle assessment: a case study in Brazil. Waste Manag. Res. 34 (10), 1026–1035. https://doi.org/10.1177/0734242x16657605.

Poon, C.S., Yu, A.T.W., Wong, A., Yip, R., 2013. Quantifying the impact of construction waste charging scheme on construction waste management in Hong Kong. J. Constr. Eng. Manag. Asce 139 (5), 466–479. https://doi.org/10.1061/(asce)co.1943-7862.0000631.

Roussat, N., Mehu, J., Dujet, C., 2009. Indicators to assess the recovery of natural resources contained in demolition waste. Waste Manag. Res. 27 (2), 159–166. https://doi.org/10.1177/0734242x08089839.

Saez, P.V., Merino, M.D., Gonzalez, A.S., Porras-Amores, C., 2013. Best practice measures assessment for construction and demolition waste management in building constructions. Resour. Conserv. Recycl. 75, 52–62. https://doi.org/10.1016/j.resconrec.2013.03.009.

Shen, L.Y., Tam, V.W.Y., Li, C.Y., 2009. Benefit analysis on replacing in situ concreting with precast slabs for temporary construction works in pursuing sustainable construction practice. Resour. Conserv. Recycl. 53 (3), 145–148. https://doi.org/10.1016/j.resconrec.2008.11.001.

Simion, I.M., Ghinea, C., Maxineasa, S.G., Taranu, N., Bonoli, A., Gavrilescu, M., 2013. Ecological footprint applied in the assessment of construction and demolition waste integrated management. Environ. Eng. Manage. J. 12 (4), 779–788.

Srour, I.M., Chehab, G.R., El-Fadel, M., Tamraz, S., 2013. Pilot-based assessment of the economics of recycling construction demolition waste. Waste Manag. Res. 31 (11), 1170–1179. https://doi.org/10.1177/0734242x13479430.

Stenis, J., 2005. Construction waste management based on industrial management models: a Swedish case study. Waste Manag. Res. 23 (1), 13–19. https://doi.org/10.1177/0734242x05050184.

Tam, V.W.Y., 2008. On the effectiveness in implementing a waste-management-plan method in construction. Waste Manag. 28 (6), 1072–1080. https://doi.org/10.1016/j.wasman.2007.04.007.

Tam, V.W.Y., Li, J.R., Cai, H., 2014. System dynamic modeling on construction waste management in Shenzhen, China. Waste Manag. Res. 32 (5), 441–453. https://doi.org/10.1177/0734242x14527636.

Tam, V.W.Y., Tam, L., Le, K.N., 2010. Cross-cultural comparison of concrete recycling decision-making and implementation in construction industry. Waste Manag. 30 (2), 291–297. https://doi.org/10.1016/j.wasman.2009.09.044.

Wang, J., Wu, H., Duan, H., Zillante, G., Zuo, J., Yuan, H., 2018. Combining Life Cycle Assessment and Building Information Modelling to account for carbon emission of building demolition waste: a case study. J. Clean. Prod. 172, 3154–3166.

Wang, J.Y., Touran, A., Christoforou, C., Fadlalla, H., 2004. A systems analysis tool for construction and demolition wastes management. Waste Manag. 24 (10), 989–997. https://doi.org/10.1016/j.wasman.2004.07.010.

Wu, H., Duan, H., Wang, J., Wang, T., Wang, X., 2015. Quantification of carbon emission of construction waste by using streamlined LCA: a case study of Shenzhen, China. J. Mater. Cycles Waste Manag. 17 (4), 637–645.

Ye, G., Yuan, H.P., Shen, L.Y., Wang, H.X., 2012. Simulating effects of management measures on the improvement of the environmental performance of construction waste management. Resour. Conserv. Recycl. 62, 56–63. https://doi.org/10.1016/j.resconrec.2012.01.010.

Yuan, F., Shen, L.Y., Li, Q.M., 2011. Emergy analysis of the recycling options for construction and demolition waste. Waste Manag. 31 (12), 2503–2511. https://doi.org/10.1016/j.wasman.2011.07.001.

Yuan, H., Wu, H., Zuo, J., 2018. Understanding factors influencing project managers' behavioral intentions to reduce waste in construction projects. J. Manag. Eng. 34 (6), 04018031.

Yuan, H.P., 2012. A model for evaluating the social performance of construction waste management. Waste Manag. 32 (6), 1218–1228. https://doi.org/10.1016/j.wasman.2012.01.028.

Yuan, H.P., 2013. Key indicators for assessing the effectiveness of waste management in construction projects. Ecol. Indic. 24, 476–484. https://doi.org/10.1016/j.ecolind.2012.07.022.

Zambrana-Vasquez, D., Zabalza-Bribian, I., Janez, A., Aranda-Uson, A., 2016. Analysis of the environmental performance of life-cycle building waste management strategies in tertiary buildings. J. Clean. Prod. 130, 143–154. https://doi.org/10.1016/j.jclepro.2016.02.048.

Zhao, W., Leeftink, R.B., Rotter, V.S., 2010. Evaluation of the economic feasibility for the recycling of construction and demolition waste in China-The case of Chongqing. Resour. Conserv. Recycl. 54 (6), 377–389. https://doi.org/10.1016/j.resconrec.2009.09.003.

Zhao, W., Ren, H., Rotter, V.S., 2011. A system dynamics model for evaluating the alternative of type in construction and demolition waste recycling center - The case of Chongqing, China. Resour. Conserv. Recycl. 55 (11), 933–944. https://doi.org/10.1016/j.resconrec.2011.04.011.

Zheng, L.N., Wu, H.Y., Zhang, H., Duan, H.B., Wang, J.Y., Jiang, W.P., Song, Q.B., 2017. Characterizing the generation and flows of construction and demolition waste in China. Constr. Build. Mater. 136, 405–413. https://doi.org/10.1016/j.conbuildmat.2017.01.055.

Appendix F: Published paper in *Architectural Science Review*

Statement of Authorship

Title of Paper	Construction and demolition waste research: A bibliometric analysis
Publication Status	[X] Published [ ] Accepted for Publication [ ] Submitted for Publication [ ] Unpublished and Unsubmitted work written in manuscript style
Publication Details	Wu, H., Zuo, J., Zillante, G., Wang, J., & Yuan, H. (2019). Construction and demolition waste research: A bibliometric analysis. *Architectural Science Review*, 62(4), 354-365. https://doi.org/10.1080/00038628.2018.1564646.

Principal Author

Name of Principal Author (Candidate)	Huanyu Wu		
Contribution to the Paper	Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft		
Overall percentage (%)	60%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	05/05/2020

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Jian Zuo		
Contribution to the Paper	Supervision, Conceptualisation, Methodology, Writing - review & editing, Validation		
Signature		Date	7/5/2020

Name of Co-Author	George Zillante		
Contribution to the Paper	Supervision, Writing - review & editing		
Signature		Date	7/5/2020

Name of Co-Author	Jiayuan Wang		
Contribution to the Paper	Supervision, Writing – review & editing.		
Signature		Date	07/05/2020

Name of Co-Author	Hongping Yuan		
Contribution to the Paper	Visualisation, Methodology, Writing - review & editing		
Signature		Date	07/05/2020

ARCHITECTURAL SCIENCE REVIEW
https://doi.org/10.1080/00038628.2018.1564646

Taylor & Francis
Taylor & Francis Group

REVIEW

Construction and demolition waste research: a bibliometric analysis

Huanyu Wu[a], Jian Zuo [a,b], George Zillante[a], Jiayuan Wang[b] and Hongping Yuan[c]

[a]School of Architecture and Built Environment, The University of Adelaide, Adelaide, South Australia, Australia; [b]School of Civil Engineering, Shenzhen University, Shenzhen, People's Republic of China; [c]School of Management, Guangzhou University, Guangzhou, Guangdong, People's Republic of China

ABSTRACT
Although construction and demolition (C&D) waste has drawn increasing attention from scholars, there is a lack of study to summarize the latest development of C&D waste research. By using a bibliometric analysis method, this study carries out a holistic review of C&D waste articles published from 1994 to 2017. It shows that the number of C&D waste articles has risen eight-times within the period. This study also demonstrates the social networks among the authors, countries, and organizations. Based on the keywords cluster analysis, the C&D waste research can be divided into five clusters, including (1) environmental concerns of C&D waste; (2) recyclability of C&D waste; (3) performance and behaviour tests of recycled products; (4) C&D waste management; and (5) C&D waste with industrial ecology. Meanwhile, the research status and future directions are discussed as well. The results would be valuable for understanding the streams and trends in C&D waste research.

ARTICLE HISTORY
Received 23 September 2018
Accepted 22 December 2018

KEYWORDS
Construction and demolition waste; built environment; waste recycling; waste management; review; bibliometric analysis

1. Introduction

Over 10 billion tons of *construction and demolition* (C&D) waste have been generated every year, among which the United States generates about 700 million tons (Jain, Powell, and Tolaymat 2015), the European Union over 800 million tons (Ajayi et al. 2016), and China around 2300 million tons (Zheng et al. 2017). Generally, C&D waste refers to wasted building materials during the construction, renovation and demolition activities. Many of the C&D wastes are recyclable (EC 2017). On the other hand, a small fraction of C&D waste might contain hazardous components bringing adverse impacts on human beings and the total environment (Roussat et al. 2008). Thus, there is a pressing need to minimize C&D waste generation and reduce its impacts on the environment.

Based on the extensive studies on C&D waste management and recycling, some reviews for outlining main research status and future trends have been conducted, though covering different research topics. Typically, those reviews can be classified into two types. The first type targets the general perspective of C&D waste management by identifying major topics in C&D waste management and recycling (Lu and Yuan 2011) and further analysing research trends (Yuan and Shen 2011). The second focuses on a specific aspect of C&D waste management and recycling. In terms of C&D waste quantification, some reviewed the methods capable of quantifying C&D waste generation (Abanda, Tah, and Cheung 2013; Wu et al. 2014), while some discussed the existing prediction models on the creep behaviour of recycled aggregate concrete (Lye et al. 2016; Silva, de Brito, and Dhir 2015a). These studies did provide valuable insights into C&D waste management and recycling by either exhibiting a big picture of the discipline or investigating some specific topics. It remains unclear, however, how C&D waste research has evolved over this period. In particular, it is not clear whether the C&D waste management discipline has reshaped compared with the findings from previous reviews, such as (Lu and Yuan 2011; Yuan and Shen 2011).

Therefore, this study attempts to carry out a holistic review on C&D waste research published from 1994 to 2017. We expect to extend previous reviews through: (1) a more comprehensive coverage both in timespan of sample articles and topics; in particular, this study will cover research in multiple disciplines, including Environmental Science and Environmental Engineering, Material Science and Engineering, Industrial Ecology, and Management Science; (2) applying a rigorous bibliometric analysis approach for the study. Bibliometric analysis has been a useful tool to gain an overall understanding about a given research field, which is deemed useful for providing further insights not previously fully grasped or evaluated (Fahimnia, Sarkis, and Davarzani 2015). With the approach, the overall development of publications in the field can be quantitatively and systematically analysed. It provides visualized graphics to quickly understand the main study streams for scholars especially those initiating their research on particular fields, such as C&D waste in the present study (Wang et al. 2016); and (3) an in-depth content analysis for gaining insights into the development trend of C&D waste research.

CONTACT Jian Zuo jian.zuo@adelaide.edu.au School of Architecture and Built Environment, The University of Adelaide, Adelaide, SA 5001, Australia; School of Civil Engineering, Shenzhen University, Shenzhen 518060, People's Republic of China; Hongping Yuan hpyuan@gzhu.edu.cn, hpyuan2005@gmail.com School of Management, Guangzhou University, Guangzhou, Guangdong 510006, People's Republic of China

2. Research method

This study aims to carry out a bibliometric analysis of C&D waste research. To achieve the research objectives, methods including bibliometric analysis, social network analysis and in-depth content analysis are employed.

2.1. Sample source and extraction

Compared to other databases (e.g. PubMed, Scopus and Google Scholar), Web of Science™ (WoS) has a comprehensive coverage in science, technology, social sciences, arts and humanities (Falagas et al. 2008). As a result, WoS has been widely adopted in bibliometric studies (i.e. Qiao, Kristoffersson, and Randrup 2018; Siva et al. 2016). WoS was also chosen for article searching and filtering in our study based on two considerations: (1) the WoS has a good coverage of articles in both waste management and waste recycling techniques; and (2) by checking the journal list in previous review articles regarding C&D waste, it is found that most of the journals are included in the WoS database.

The advanced search function provided by the WoS Core collection database was employed to retrieve related publications. The searching process was carried out on 1 March 2018. The searching strategy is: *(TS = ('construction waste' OR 'demolition waste' OR 'construction and demolition waste' OR 'C&D waste')) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article); Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = All years*.

We indented to track back C&D waste publications as early as possible. However, it is founded that only publications since 1994 are documented by the WoS database. Therefore, the research period was confirmed as from 1994 to 2017.

2.2. Research procedure for analysis

A comprehensive procedure, as shown in Figure 1, was followed to conduct a bibliometric analysis of C&D waste publications.

Firstly, a basic bibliometric analysis was carried out to quantitatively understand the overall research status of C&D waste. The bibliometric analysis has been widely adopted to map the existing literature and measure research progress in a given field (van Raan 2005). The aspects of the body of the literature by the bibliometric analysis method include both quantitative information and qualitative data (Wang et al. 2016). Particularly, it includes quantitative and visual processes to identify patterns and dynamics in scientific publications (Pritchard 1969). In our study, a series of quantitative analyses were conducted to understand the overall status of C&D waste. The analyses included: (1) article publication trend; (2) the distribution of published journals; (3) the analysis of authors; (4) the analysis of countries; and (5) the analysis of author organizations.

Secondly, social network analyses were conducted to depict the relationship among authors, countries and organizations. Social network analysis is designed to model the dynamics between focus and relationships which has been employed in bibliometric analysis studies (Prell 2012; Scott 2017). In the context of bibliometric analysis, this method has been employed to highlight the relationship between various nodes in the networks (e.g. countries, institutions and authors in a given subject)

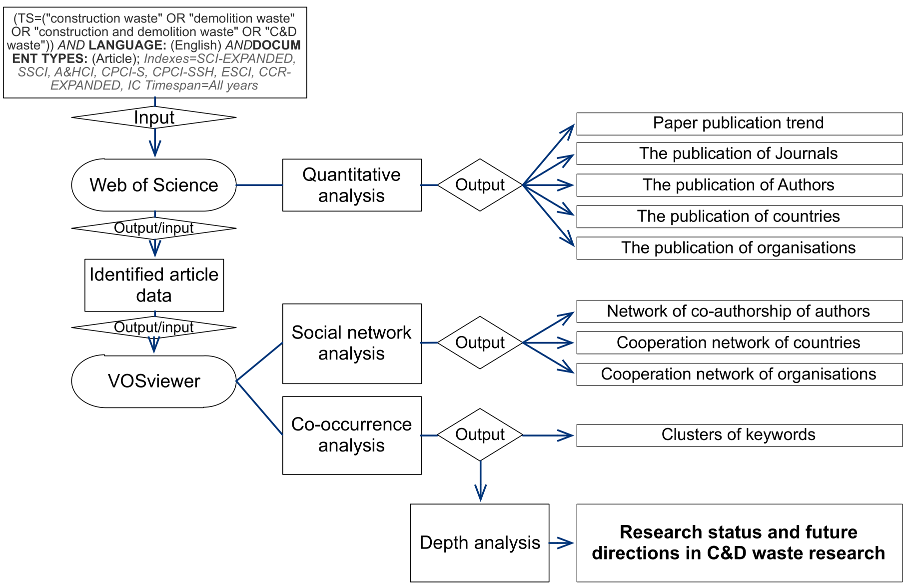


Figure 1. Research procedure.

(Wang et al. 2016). This is completed by using a user-friendly software VOSviewer. Normally, these analyses should have based on several rules, including: co-authorship analysis meaning that the relatedness of items is determined based on their number of co-authored articles, co-occurrence analysis meaning that the relatedness of items is determined based on the number of articles in which they occur together, and full counting referring to that each co-authorship, co-occurrence and bibliographic coupling link have the same weighting.

Thirdly, clustering analysis was carried out to examine the comprehensive relationship between keywords in articles. The approach has been used to search management information systems and analyse the research trends (Du et al. 2014), discover research hotpots (Du et al. 2015) and identify the evolution of research topics (Li, Wang, and Ho 2011). Since data visualization plays a crucial role in network research (Wang et al. 2016), the cluster map was conducted through VOSviewer as well. To better identify the corn keywords and their relationships, some common words (e.g. construction, demolition, deconstruction, building construction, construction project, construction sector, road, urban, city, construction industry, waste, construction waste, demolition waste, construction and demolition waste, C&D waste, solid waste, construction materials) and region/country names (e.g. U.S.A, U.K., Australia, Hong Kong, China, Portugal, Japan, Malaysia, Norway, etc.) have been eliminated.

Finally, based on the keywords cluster analysis, an in-depth content analysis was conducted to review selected articles for gaining insights into the development trend of C&D waste research. Based on the analysis, the research gaps and proposed future research opportunities were discussed.

3. Overall status of C&D waste research

3.1. Number of published articles

3.1.1. Amount of published articles

Through the search in WoS, it is found that 1027 C&D waste-related articles are published between 1994 and 2017 (see Figure 2). Before 2007 the number of annual articles is less than 20, but the number has risen eight times in the past decade and reached 178 in 2016.

3.1.2. Number of articles published by journals

The results in Table 1 show that more than half of the C&D waste-related articles were published on 10 journals; particularly, *Construction and Building Materials* and *Waste Management* each publishes more than 100 articles, and *Journal of Cleaner Production* and *Resources Conservation and Recycling* each publishes more than 50 articles. These journals make significant contributions to the dissemination of C&D waste research.

3.2. The publishing performance of authors

3.2.1. Number of articles by authors

The results show that during the period 74 authors are significant in publishing C&D waste research, each with more than 5 published articles (see Table 2). Among the top 10 most productive authors, J. De Britto publishes 48 articles and builds up 1289 citations, followed by V.W.Y. Tam (28 articles, 618 citations) and C.S. Poon (22 articles, 639 citations).

3.2.2. Co-authorship among authors

Figure 3 shows the network of co-authorship among authors in C&D waste research. It can be observed that the network mainly consisted of eight clusters based on the authorship analysis. Each cluster is developed around one or two core authors. Cluster 1 is centred by F. Agrela and J. Ayuso, and it links closely with Cluster 5 (presented by C.S. Poon) and Cluster 6 (presented by J. De Brito). Cluster 3, Cluster 4 and Cluster 7 are presented by V.W.Y. Tam, H.P. Yuan and J.Y. Wang. This network map clearly shows the most active research groups and the authorship relations among the authors contributing to C&D waste research.

Table 1. Ten journals publishing most C&D waste articles.

Journals	Number of articles
Construction and Building Materials	120
Waste Management	109
Journal of Cleaner Production	83
Resources Conservation and Recycling	79
Waste Management Research	45
Journal of Materials in Civil Engineering	24
Cement Concrete Composites	14
Materials and Structures	13
Building Research and Information	12
Journal of Hazardous Materials	12

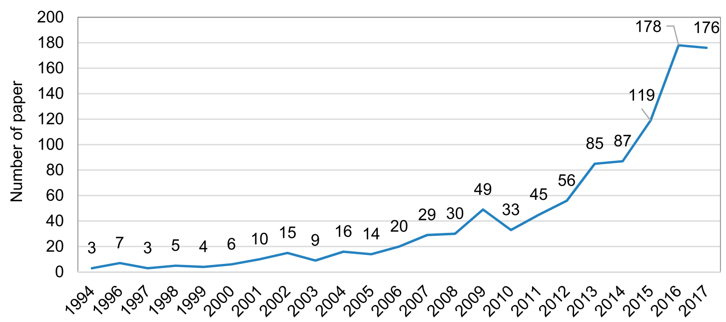


Figure 2. Number of C&D waste articles published over 1994–2017.

Table 2. Authors publishing most C&D waste articles (ranking based on the number of published articles).

Authors	Affiliation	Region	Number of articles	Citations
De Britto, J.	University of Lisbon	Portugal	48	1289
Tam, V.W.Y.	Western Sydney University	Australia	28	618
Poon, C.S.	Hong Kong Polytech University	Hong Kong, China	22	639
Ayuso, J.	University of Córdoba	Spain	18	351
Wang, J.Y.	Shenzhen University	Mainland China	18	301
Agrela, F.	University of Córdoba	Spain	17	383
Evangelista, L.	University of Stavanger	Norway	16	325
Perez, I.	University of A Coruña	Spain	14	134
Yuan, H.P.	Southwest Jiaotong University	Mainland China	14	447
Barbudo, A.	University of Córdoba	Spain	12	199

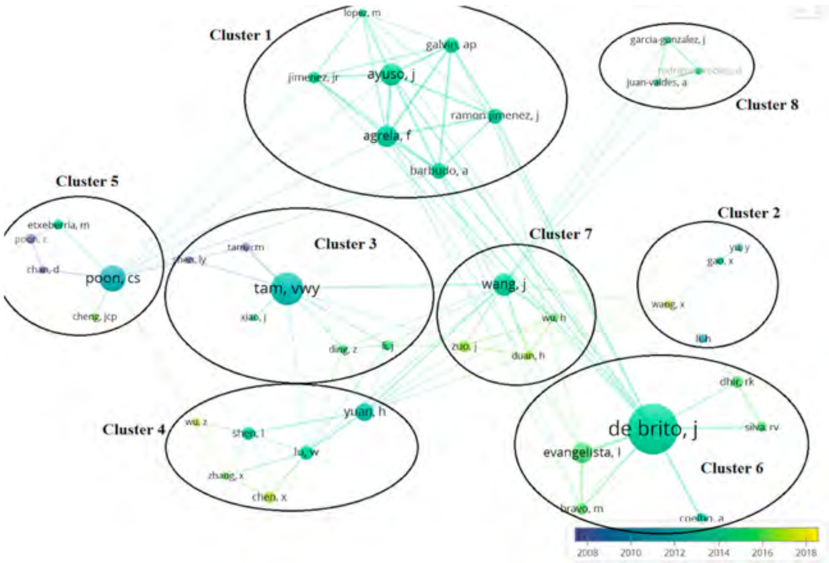


Figure 3. Network of authorship among authors in C&D waste research.
Note: The size of the node is determined by the number of published articles.

3.3. Analysis of author regions

3.3.1. Number of articles and citations by regions

Table 3 shows the top 10 regions contributing to C&D waste research. Apparently, China has been in a leading position in both the number of published articles and citations in C&D waste research. Spain is also influential with 150 published articles and 2156 citations. It is notable that although some regions publish more articles, their total citations are less, for example, Brazil with 61 published articles but only 567 citations. This list for the regions contributing to most C&D waste research is quite different with the findings in a study conducted almost a decade ago (Yuan and Shen 2011), when developing regions such as China, Spain and Brazil did not publish many articles in this area. This reveals a significant geographical change of C&D waste research within the last decade.

Table 3. Regions contributing to most C&D waste research (ranking based on the number of articles).

Regions	Number of articles	Citations
China	199	3465
Spain	150	2156
Australia	86	1224
England	69	1011
U.S.A	68	1353
Brazil	61	567
Portugal	59	1370
Germany	41	689
Netherlands	39	803
Italy	37	616

3.3.2. Co-authorship among regions

Figure 4 shows the co-authorship among regions in C&D waste research, which represents the cooperation network among authors from different regions. The size of nodes is determinate by the strength of links; that is, a region with a larger node means it reaches more cooperation with C&D waste scholars from other regions. The results show that the node size of England is almost equal to that of China although England only publishes a third of articles compared to China. In contrast, the node size of Spain is comparatively small considering its large publication amount. It reveals that China, England, U.S.A and

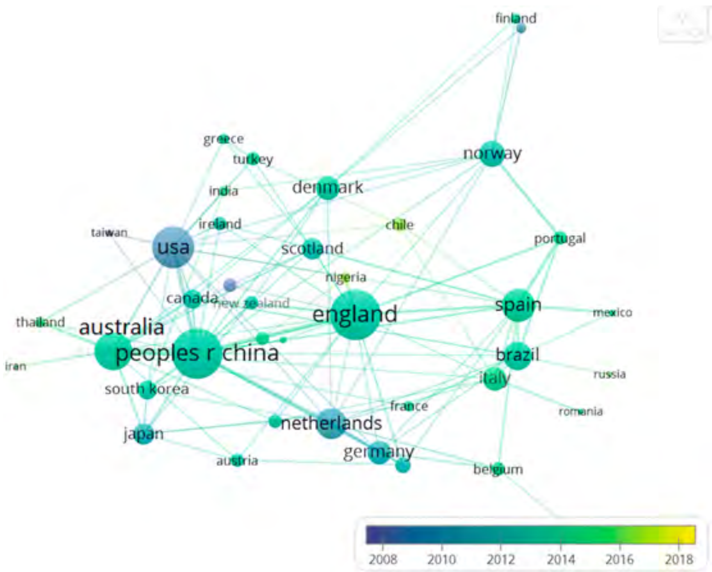


Figure 4. Research cooperation network among authors from different regions.
Note: The size of node is determined by the strength of links.

Australia are quite active in building a cooperative network with scholars from other regions. Meanwhile, from a time trend, U.S.A, Netherlands, Germany and Japan started the research of C&D waste quite earlier and the main outputs were around 2008, while China, England, Australia, Spain and Brazil follow this trend and their outcomes were mainly around 2014.

3.4. Analysis of author organizations

3.4.1. Publications of organizations

According to the analysis, a total of 925 organizations worldwide have published C&D waste articles, among which 57 organizations have published more than 5 articles (see Table 4). The Hong Kong Polytech University in China is the top contributor by contributing 65 articles and attracted more than 2000 citations. Furthermore, 3 organizations, including the University of Lisbon in Portugal, Shenzhen University in mainland China and the University of Córdoba in Spain also contribute significantly, with 27 articles, 25 articles and 25 articles published, respectively.

Table 4. Organizations published most C&D waste articles (ranking based on the number of articles).

Author organization	Number of articles	Citations
Hong Kong Polytechnic University, Hong Kong, China	65	2094
University of Lisbon, Portugal	27	274
Shenzhen University, mainland China	25	315
University of Córdoba, Spain	25	462
Delft University of Technology, Netherlands	19	163
Technical University of Lisbon, Portugal	18	693
University of A Coruña, Spain	18	155
Western Sydney University, Australia	17	241
Tongji University, mainland China	17	206
The University of Hong Kong, Hong Kong, China	16	459

3.4.2. Co-authorship among author's affiliations

The cooperative relationship among author organizations is also analysed (see Figure 5). Similarly, the size of the node is determined by the strength of links; that is, an organization with a larger node means it has more cooperation with other organizations in C&D waste research. It shows that some Chinese institutes (e.g. Hong Kong Polytech University, Shenzhen University, Tongji University, Chongqing University, and University of Hong Kong) trend to build more cooperation with other institutes. Australia's Western Sydney University also have built comparative more links with other institutes. In contrast, some institutes from Portugal (e.g. University of Lisbon, Technical University of Lisbon) and Spain (e.g. University of Córdoba, University of A Coruña) seem to be more inclined to conduct C&D waste research internally with less links with other institutes.

4. Research status based on keywords cluster analyses

Based on the results of cluster analysis, the keywords in C&D waste articles can be classified into five clusters (see Figure 6). The clusters are *Cluster (1) Environmental impacts of C&D waste; Cluster (2) Recyclability of C&D waste; Cluster (3) Performance and behaviour tests of recycled products; Cluster (4) C&D waste management; Cluster (5) C&D waste from the perspective of interdisciplinary*. Subsequently, these clusters are discussed in detail to construct a holistic view of the state-of-the-art C&D waste research.

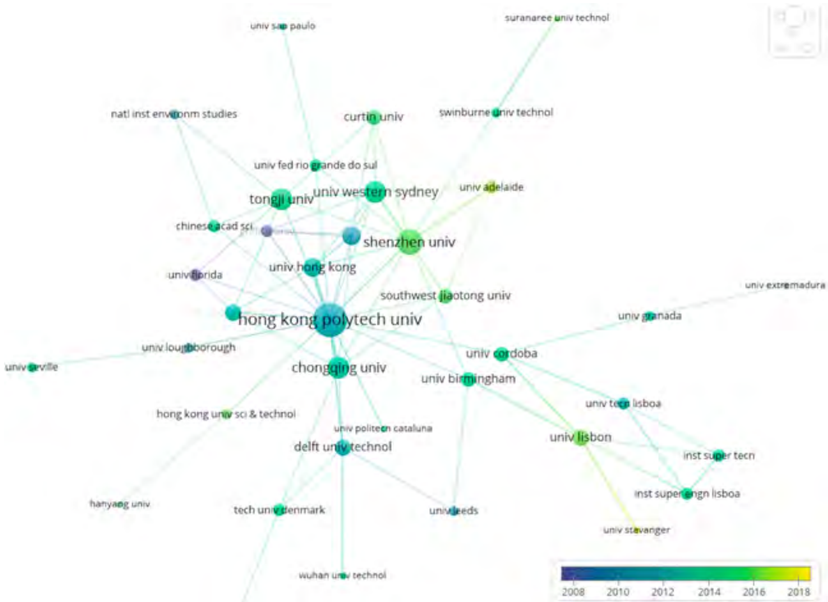


Figure 5. Research cooperation network among institutions.
Note: The size of node is determined by the strength of links.

4.1. Cluster (1): environmental impacts of C&D waste

The first cluster is related to the environmental concerns of C&D waste, which received significant attention from the environmental science and engineering discipline. According to the keywords identified in the cluster analysis (Table 5), articles in this cluster attempted to answer three main questions: (1) what pollutant compositions are contained in C&D waste? (2) how the pollutants in C&D waste would affect the surrounding environment? and (3) how to control and mitigate the pollution of C&D waste composition?

Existing studies have reported that C&D waste may contain multiple pollutant compositions, e.g. heavy metals and organic matter (Jang and Townsend 2001; Van Praagh and Modin 2016). These pollutant compositions would affect the surrounding environment (e.g. water, groundwater, soils) via multiple mechanisms (e.g. sorption, adsorption, release, immobilization, incineration, pyrolysis, etc.) and approaches (e.g. leachate, biomass, landfill gas, etc.) (Lee et al. 2008; Shin, Na, and Kim 2016). There are two main research aspects in this area: (1) identification of pollutant composition of C&D waste (Jang and Townsend 2001; Van Praagh and Modin 2016; Duan et al. 2016); (2) control and mitigation of pollution for C&D waste (Delay et al. 2007; Iden et al. 2008; Shin, Na, and Kim 2016).

4.2. Cluster (2): recyclability of C&D waste

The second cluster is about the recyclability of C&D waste, mostly conducted from the perspective of material science. According to the keywords identified in the cluster analysis (Table 6), studies under this cluster mainly focus on the following questions: (1) what recycled products can be made from C&D waste? (2) what are the application situations for C&D waste recycled products? and (3) how to test the performance of recyclable waste materials and recycled products?

It is widely recognized that some C&D waste materials (e.g. concrete, mortar, brick and glass) are recyclable. For instance, concrete and brick can be used to produce recycled aggregate (Garcia-Gonzalez et al. 2014; Vegas et al. 2015); mortars can be used to produce recycled sand (Ulsen et al. 2013). Recycled C&D waste products (e.g. recycled aggregate, recycled sand, crushed brick aggregates and recycled glass blends) can be used in different contexts, e.g. pavement base or subbase, hot mix asphalt, mortar components, additional materials. Previous studies have focused on three main aspects: (1) understanding recyclable C&D waste materials (Garcia-Gonzalez et al. 2014), (Vegas et al. 2015); (2) understanding recycled products of C&D waste (Kumar 2017; Hou et al. 2016); and (3) making the use of C&D recycled products (Xuan, Molenaar, and Houben 2016; Arulrajah et al. 2013; Belagraa, Beddar, and Bouzid 2017).

4.3. Cluster (3): performance and behaviour tests of waste materials and recycled products

The third cluster is related to the performance and behaviour tests of waste and recycled products from environment science and materials science fields. According to the keywords identified in the cluster analysis (Table 7), studies under this cluster

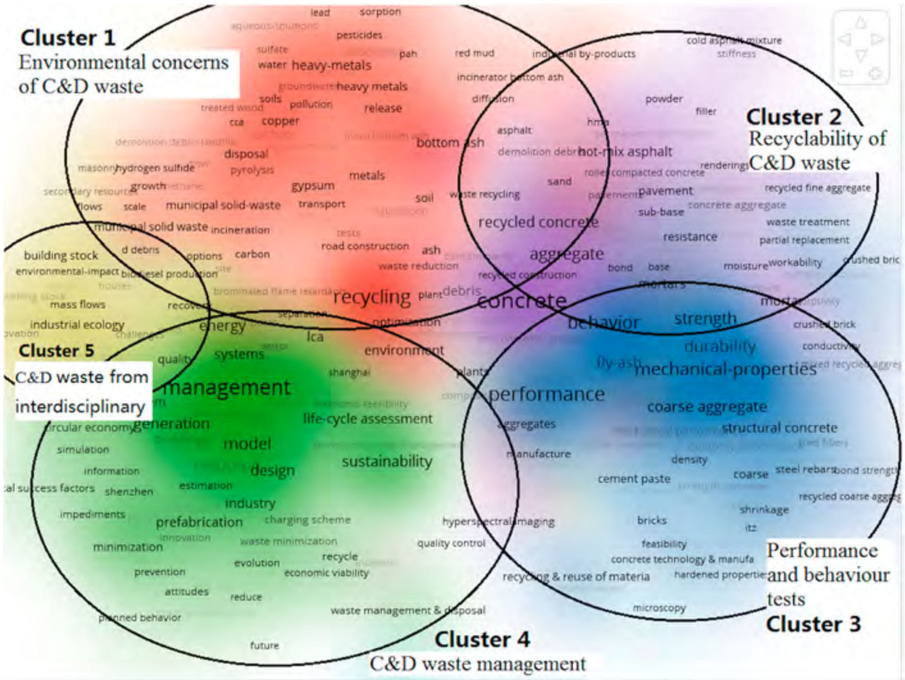


Figure 6. Clusters based on keyword analysis.

Table 5. Keywords under cluster (1).

Classification	Keywords
Pollutant compositions	Heavy metals (e.g. copper and chromium), organic matter (e.g. polycyclic aromatic hydrocrack, carbon, methane, sulfuret and hydrogen sulphide)
Effect mechanism	Sorption, adsorption, release, immobilization, incineration, pyrolysis
Impact approach	Leachate, biomass, landfill gas, pesticides (come from the demolition waste of abandoned pesticide manufacturing plant)
Affected surroundings	Water, groundwater, soils
Testing methods	Leaching tests

Table 6. Keywords under cluster (2).

Classification	Keywords
Recyclable waste materials	Concrete, cement mortar, sand, glass waste
Recycled products	Recycled aggregate, recycled fine aggregate, recycled sand, recycled glass, hot mix asphalt
Use of recycled products	Subbase, pavement, reclaimed asphalt pavement, filler

mainly focus on the following questions: (1) how does C&D waste or recycled products behave? (2) how to exam the performance of C&D waste or recycled products? and (3) how to improve the performance of C&D recycled products?

Studies have been conducted to test the performance of C&D waste and recycled products (particularly recycled aggregate) (Anastasiou, Filikas, and Stefanidou 2014; da Silva et al. 2014; Belagraa, Beddar, and Bouzid 2017; Tam, Kotrayothar, and Xiao 2015). These studies have been conducted from various perspectives such as efficiency of utilization, physical and mechanical properties/performance, and mechanical behaviours. In addition, other aspects such as macroscopic and microstructural properties of recycled concrete have been studied. Meanwhile, some studies focus on specific performance testing (e.g. deformation, tensile strength, compressive strength, resistance, durability, stiffness, etc.) of recycled aggregate. These studies can be classified into two groups: (1) developing performance test indicator system for testing the performance of recycled products (Zega, Villagran-Zaccardi, and Di Maio 2010; Matias et al. 2013; da Silva et al. 2014; Belagraa, Beddar, and Bouzid 2017); (2) conducting specific performance tests, such as strength, durability, stiffness, etc. (Tam, Kotrayothar, and Xiao 2015; Silva, de Brito, and Dhir 2015b).

Table 7. Keywords under cluster (3).

Classification	Keywords
Performance category	Behaviour, performance, mechanical properties, physical properties, engineering properties, mechanical behaviour, permanent deformation, curing condition
Performance indicators	Strength, compressive strength, bond strength, durability, stiffness, porosity, conductivity, microstructure, density, elasticity, modulus of elasticity, hardened properties

Table 8. Keywords under cluster (4).

Classification	Keywords
Waste generation	Generation, waste generation rate, quantification, estimation
Waste reduction	Reduction, minimizationsDesign, on siteAttitudes, planned behaviourCharging scheme
Economic performance	Circular economy, economic feasibility, economic viability
Information tech	Information, GIS, BIM, Big Data

4.4. Cluster (4): C&D waste management

The fourth cluster is about how to manage C&D waste. According to the keywords identified in the cluster analysis (Table 8), studies under this cluster mainly focus on the following questions: (1) how to estimate the generation of C&D waste? (2) how to minimize the generation of C&D waste? (3) how to assess the performance of C&D waste management system? and (4) how to apply information technology tools in C&D waste management and recycling?

Appropriate management measures can help to reduce the waste generation, enhance waste reuse and recycling and minimize the waste disposed of in landfills. This can further help to reduce the environmental concerns caused by the massive C&D waste. The C&D waste management studies can be divided into four groups: (1) quantifying of C&D waste generation, including conduct surveys of C&D waste generation in particular region (Bergsdal, Bohne, and Brattebo 2007; Wu et al. 2016a ; Zheng et al. 2017), investigate the waste generation rate (Lu et al. 2011; Li et al. 2013; Malia et al. 2013; Lu et al. 2017), and develop C&D waste generation estimation models (Won, Cheng, and Lee 2016; Wu et al. 2016a); (2) reducing the generation of C&D waste via management measures (Wang, Li, and Tam 2014; Wang et al. 2010; Lu and Yuan 2010); (3) assessing the management performance of C&D waste (Zhao, Leeftink, and Rotter 2010; Coelho and de Brito 2013; Jung et al. 2015); and (4) adopting information techs in C&D waste research (Lu et al. 2016; Wu et al. 2016b).

4.5. Cluster (5): C&D waste following the interdisciplinary approach

The fifth cluster is about the C&D waste from the perspective of interdisciplinary. This cluster is comparatively smaller than others, following an interdisciplinary approach combining environment, economy and management. The industrial ecology concerns multiple issues in an industry system, such as materials flows, life cycle impacts and dynamic of technology in industry (Erkman 1997). Based on the characterization of these keywords, studies in this field attempted to answer main questions such as, how does C&D waste flow from generation to final disposal? What are impacts coupled in the life cycle of C&D waste? How to understand the trend or dynamic of C&D waste? Currently, studies toward C&D waste from an industrial ecology perspective mainly focus on following aspects: (1) tracking C&D waste materials flow from the waste generation to final disposal (Huang and Hsu 2003; Blengini and Garbarino 2010; Wiedenhofer et al. 2015; Hu, van der Voet, and Huppes 2010); (2) life cycle assessment, including developing models to assess the life cycle impacts of processing C&D waste (Simion et al. 2013; Marzouk and Azab 2014) and assessing the life cycle energy and resource efficiency of processing C&D waste (Mercader-Moyano and Ramirez-de-Arellano-Agudo 2013; Rivero, Sathre, and Navarro 2016; Wang et al. 2018; Wu et al. 2015).

5. Future research directions

5.1. Research directions in environmental concerns of C&D waste

It is frequently discussed in previous studies that C&D waste may contain heavy metals (Jang and Townsend 2001; Van Praagh and Modin 2016) and organic matters (Duan et al. 2016). Most updated studies found that C&D waste in landfills or treatment facilities may also contain toxicity compositions which were generated from an abandoned pesticide manufacturing plant. The environmental impacts of these C&D waste are very complex and uncertain; the mixed hazardous substances would cause serious harms to the environment (Huang et al. 2016, 2017). Unfortunately, the understanding of the complexity of environmental impacts from C&D waste remain limited and few measures have been developed to control these pollutants (Kalbe et al. 2008; Cabalar, Abdulnafaa, and Karabash 2016). This is mainly because the methods that used to understand these issues are heavily reliant on traditional methods such as leaching test (Engelsen, van der Sloot, and Petkovic 2017; Galvin et al. 2012; Van Praagh and Modin 2016). Therefore, future directions can consider following aspects: (1) making efforts on understanding the complexity of pollutants consisted in C&D waste; (2) developing comprehensive pollutants control measures for treating and disposal of C&D waste; and (3) developing more testing methods to assess environmental concerns caused by C&D waste.

5.2. Research directions in recyclability of C&D waste

As analysed previously, significant studies have been conducted to produce recycled products. The use of recycled products of C&D waste has been discussed in many articles, where these recycled products are used in many applications (Arulrajah et al. 2013; Choudhary, Shah, and Bishnoi 2016; Belagraa, Beddar, and Bouzid 2017). Previous studies have revealed that recycled C&D waste products are gaining widespread attention recently to be used as a construction material both from material and structural point of view. However, to use recycled C&D waste products like recycled aggregate as a structural material need to be characterized very precisely its quality and properties (Behera et al. 2014). Hence, research directions are (1) exploring recyclable C&D waste materials, such as timber, carpet, plaster, etc.; (2) improving the performance of recycled C&D products in term of strength, durability, stiffness, and so on (Silva, de Brito, and Dhir 2015b; Tam, Kotrayothar, and Xiao 2015; Belagraa, Beddar, and Bouzid 2017; Dantas, Leite, and Nagahama 2013; Younis and Pilakoutas 2013; Correia, de Brito, and Pereira 2006); and (3) developing more application situations for recycled C&D waste products.

5.3. Research directions in C&D waste management

In order to minimize the generation of C&D waste, multiple studies reported practical experiences and proposed measures (e.g. waste charging scheme) from various countries (Esin and Cosgun 2007; Begum et al. 2007; Tam and Tam 2008; Ajayi et al. 2016). Most current studies are concentrated on the waste reuse or recycling, while only little efforts have been made to prevent the generation of C&D waste from design stage (Wang, Li, and Tam 2014). There are multiple factors would affect the success of C&D waste management, such as the attitudes and behaviour of stakeholders, economic incentives, and so on (Lu and Yuan 2010). However, there are few research efforts made on using economic incentives (e.g. waste disposal charging fee) to prevent the generation of waste and few knowledge of understanding the social aspects (e.g. human factors) in C&D waste management system (Yuan and Shen 2011). Meanwhile, with the development of Information technologies, some tools such as GIS, BIM, and Big Data have been limitedly applied in C&D waste research (Lu et al. 2016; Wu et al. 2016), while these studies mainly use these techs to improve the research quality and accurately. Given current research progress and limitations, there are some research directions in terms of improving C&D waste management: (1) reducing waste generation from early management stage; (2) developing C&D waste disposal charging system; (3) developing practical performance evaluation criteria (including social aspect) for C&D waste management; and (4) exploring the use of information techs in improving the C&D waste management.

5.4. Directions of C&D waste interdisciplinary research

Several studies tracked the mass flow or material flow of C&D waste, and assessed the life cycle energy or resource efficiency of C&D waste in different regions. However, the research scopes of those studies have limited on certain C&D waste materials rather than a comprehensive waste package as C&D waste concluding multiple waste materials and the characterizations of these materials are dramatic different, which need to be investigated comprehensively (Duan et al. 2016). Meanwhile, C&D waste processing as a local-closed issue (generation and treatment of the waste in one place), which may overlook the dynamic and mobility of the recycling activities. As in many cases, some materials of C&D waste (e.g. metals, plastic, glass, etc.) may transport across the border to be treated in other cities or even countries. In particular, the heavy concrete/brick waste would be transported to be dumped in other regions (ABC 2017). Therefore, future studies can consider the following aspects: (1) extending the research boundary of C&D waste flows; and (2) understanding the dynamics and mobility during the life cycle of C&D waste procedure.

6. Conclusions

A comprehensive bibliometric analysis was conducted to review C&D waste articles published in the WoS database; 1027 C&D waste articles published from 1994 to 2017 were reviewed and analysed. Results showed that C&D waste had attracted increasing research efforts in past decades where the number of C&D waste articles increased eight times. By measuring the main authors' contributions, it has been found that researchers from China, Spain, and Brazil contributed a large portion of publications. This reveals a geographical evolution of C&D waste research from developed regions to developing regions within the last decade. Meanwhile, this study describes the social networks among the authors, countries and organizations. Results showed that China, England, U.S.A and Australia are quite active in building a cooperative network with scholars from other regions.

Based on the keywords cluster analysis, it is found that C&D waste research can be divided into five clusters: (1) Environmental concerns of C&D waste; (2) Recyclability of C&D waste; (3) Performance and behaviour tests of recycled products; (4) C&D waste management; and (5) C&D waste from the perspective of interdisciplinary. Under different clusters, the research interests and focus vary dramatically. The future directions are identified as well. For instance, in terms of environmental concerns of C&D waste, future directions include: (1) making efforts on understanding the complexity of pollutants consisted in C&D waste; (2) developing comprehensive pollutants control measures for treating and disposal of C&D waste; and (3) developing more testing methods to assess environmental concerns caused by C&D waste. In terms of recyclability of C&D waste, future research efforts can be directed to (1) exploring recyclable C&D waste materials, such as timber, carpet, plaster, etc.; (2) improving the performance of recycled C&D products in term of strength, durability, stiffness, and so on; and (3) developing more application situations for recycled C&D waste products. In terms of C&D waste management, potential research directions include (1) reducing waste generation from the early management stage; (2) developing C&D waste disposal charging system; (3) developing practical performance evaluation criteria for C&D waste management; and (4) exploring the use of information techniques in improving C&D waste management. In terms of studying C&D waste from an interdisciplinary perspective, future directions include (1) extending the research boundary of C&D waste flows; and (2) understanding the dynamics and mobility during the life cycle of C&D waste management procedure.

The information revealed in this study is valuable for helping researchers to understand the streams and trends in C&D waste research. It contributes to the knowledge as it extends previous reviews through a more comprehensive coverage both in timespan of sample articles and topics. Meanwhile, it provides visualized graphics to quickly understand the main study streams for scholars especially those initiating their research on particular fields.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The study was financially supported by the National Natural Science Foundation of China [grant number 71573216], the Sichuan Province Science and Technology Support Program [grant number 2017ZR0150], and the Shenzhen Science and Technology Plan [grant number JCYJ2016052017 3631894].

ORCID

Jian Zuo http://orcid.org/0000-0002-8279-9666

References

Abanda, F. H., J. H. M. Tah, and F. K. T. Cheung. 2013. "Mathematical Modelling of Embodied Energy, Greenhouse Gases, Waste, Time–Cost Parameters of Building Projects: A Review." *Building and Environment* 59: 23–37. doi:10.1016/j.buildenv.2012.07.014.

ABC. 2017. Trashed. *4corners*. Published August 7, 2017. http://www.abc.net.au/4corners/trashed/8770146.

Ajayi, S. O., L. O. Oyedele, O. O. Akinade, M. Bilal, H. A. Owolabi, H. A. Alaka, and K. O. Kadiri. 2016. "Reducing Waste to Landfill: A Need for Cultural Change in the UK Construction Industry." *Journal of Building Engineering* 5: 185–193. doi:10.1016/j.jobe.2015.12.007.

Anastasiou, E., K. G. Filikas, and M. Stefanidou. 2014. "Utilization of Fine Recycled Aggregates in Concrete with Fly Ash and Steel Slag." *Construction and Building Materials* 50: 154–161. doi:10.1016/j.conbuildmat.2013.09.037.

Arulrajah, A., J. Piratheepan, M. M. Disfani, and M. W. Bo. 2013. "Geotechnical and Geoenvironmental Properties of Recycled Construction and Demolition Materials in Pavement Subbase Applications." *Journal of Materials in Civil Engineering* 25 (8): 1077–1088. doi:10.1061/(asce)mt.1943-5533.0000652.

Begum, R. A., C. Siwar, J. J. Pereira, and A. H. Jaafar. 2007. "Implementation of Waste Management and Minimisation in the Construction Industry of Malaysia." *Resources, Conservation and Recycling* 51 (1): 190–202. doi:10.1016/j.resconrec.2006.09.004.

Behera, M., S. K. Bhattacharyya, A. K. Minocha, R. Deoliya, and S. Maiti. 2014. "Recycled Aggregate from C&D Waste & Its Use in Concrete – A Breakthrough Towards Sustainability in Construction Sector: A Review." *Construction and Building Materials* 68: 501–516.

Belagraa, L., M. Beddar, and A. Bouzid. 2017. "Marble Fillers Effect on the Mechanical Performance of a Recycled Aggregate Concrete." *Environmental Engineering and Management Journal* 16 (1): 197–204.

Bergsdal, H., R. A. Bohne, and H. Brattebo. 2007. "Projection of Construction and Demolition Waste in Norway." *Journal of Industrial Ecology* 11 (3): 27–39. doi:10.1162/jiec.2007.1149.

Blengini, G. A., and E. Garbarino. 2010. "Resources and Waste Management in Turin (Italy): The Role of Recycled Aggregates in the Sustainable Supply Mix." *Journal of Cleaner Production* 18 (10–11): 1021–1030. doi:10.1016/j.jclepro.2010.01.027.

Cabalar, A. F., M. D. Abdulnafaa, and Z. Karabash. 2016. "Influences of Various Construction and Demolition Materials on the Behavior of a Clay." *Environmental Earth Sciences* 75 (9): 9. doi:10.1007/s12665-016-5631-4.

Choudhary, A., V. Shah, and S. Bishnoi. 2016. "Effect of Low Cost Fillers on Cement Hydration." *Construction and Building Materials* 124: 533–543. doi:10.1016/j.conbuildmat.2016.07.088.

Coelho, A., and J. de Brito. 2013. "Economic Viability Analysis of a Construction and Demolition Waste Recycling Plant in Portugal – Part I: Location, Materials, Technology and Economic Analysis." *Journal of Cleaner Production* 39: 338–352. doi:10.1016/j.jclepro.2012.08.024.

Correia, J. R., J. de Brito, and A. S. Pereira. 2006. "Effects on Concrete Durability of Using Recycled Ceramic Aggregates." *Materials and Structures* 39 (2): 169–177. doi:10.1617/s11527-005-9014-7.

Dantas, A. T. A., M. B. Leite, and K. D. Nagahama. 2013. "Prediction of Compressive Strength of Concrete Containing Construction and Demolition Waste Using Artificial Neural Networks." *Construction and Building Materials* 38: 717–722. doi:10.1016/j.conbuildmat.2012.09.026.

da Silva, V. M., L. C. Gois, J. B. Duarte, J. B. da Silva, and W. Acchar. 2014. "Incorporation of Ceramic Waste into Binary and Ternary Soil-cement Formulations for the Production of Solid Bricks." *Materials Research-Ibero-American Journal of Materials* 17 (2): 326–331. doi:10.1590/s1516-14392014005000014.

Delay, M., T. Lager, H. D. Schulz, and F. H. Frimmel. 2007. "Comparison of Leaching Tests to Determine and Quantify the Release of Inorganic Contaminants in Demolition Waste." *Waste Management* 27 (2): 248–255. doi:10.1016/j.wasman.2006.01.013.

Du, H., B. Li, M. A. Brown, G. Mao, R. Rameezdeen, and H. Chen. 2015. "Expanding and Shifting Trends in Carbon Market Research: A Quantitative Bibliometric Study." *Journal of Cleaner Production* 103: 104–111.

Du, H., N. Li, M. A. Brown, Y. Peng, and Y. Shuai. 2014. "A Bibliographic Analysis of Recent Solar Energy Literatures: The Expansion and Evolution of a Research Field." *Renewable Energy* 66: 696–706.

Duan, H., D. F. Yu, J. Zuo, B. Yang, Y. K. Zhang, and Y. N. Niu. 2016. "Characterization of Brominated Flame Retardants in Construction and Demolition Waste Components: HBCD and PBDEs." *Science of the Total Environment* 572: 77–85. doi:10.1016/j.scitotenv.2016.07.165.

Engelsen, C. J., H. A. van der Sloot, and G. Petkovic. 2017. "Long-term Leaching from Recycled Concrete Aggregates Applied as Sub-base Material in Road Construction." *Science of the Total Environment* 587–588: 94–101. doi:10.1016/j.scitotenv.2017.02.052.

Erkman, S. 1997. "Industrial Ecology: An Historical View." *Journal of Cleaner Production* 5 (1–2): 1–10.

Esin, T., and N. Cosgun. 2007. "A Study Conducted to Reduce Construction Waste Generation in Turkey." *Building and Environment* 42 (4): 1667–1674. doi:10.1016/j.buildenv.2006.02.008.

European Commission. 2017. *Construction and Demolition Waste, Waste Streams, Environment*. http://ec.europa.eu/environment/waste/construction_demolition.htm.

Fahimnia, B., J. Sarkis, and H. Davarzani. 2015. "Green Supply Chain Management: A Review and Bibliometric Analysis." *International Journal of Production Economics* 162: 101–114. doi:10.1016/j.ijpe.2015.01.003.

Falagas, M. E., E. I. Pitsouni, G. A. Malietzis, and G. Pappas. 2008. "Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and Weaknesses." *The FASEB Journal* 22 (2): 338–342.

Galvin, A. P., J. Ayuso, J. R. Jimenez, and F. Agrela. 2012. "Comparison of Batch Leaching Tests and Influence of pH on the Release of Metals from Construction and Demolition Wastes." *Waste Management* 32 (1): 88–95. doi:10.1016/j.wasman.2011.09.010.

Garcia-Gonzalez, J., D. Rodriguez-Robles, A. Juan-Valdes, J. M. Moran-del Pozo, and M. I. Guerra-Romero. 2014. "Pre-saturation Technique of the Recycled Aggregates: Solution to the Water Absorption Drawback in the Recycled Concrete Manufacture." *Materials* 7 (9): 6224–6236. doi:10.3390/ma7096224.

Hou, Y. Q., X. P. Ji, L. Zou, S. Liu, and X. L. Su. 2016. "Performance of Cement-stabilised Crushed Brick Aggregates in Asphalt Pavement Base and Subbase Applications." *Road Materials and Pavement Design* 17 (1): 120–135. doi:10.1080/14680629.2015.1064466.

Hu, M. M., E. van der Voet, and G. Huppes. 2010. "Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing." *Journal of Industrial Ecology* 14 (3): 440–456. doi:10.1111/j.1530-9290.2010.00245.x.

Huang, S. L., and W. L. Hsu. 2003. "Materials Flow Analysis and Energy Evaluation of Taipei's Urban Construction." *Landscape and Urban Planning* 63 (2): 61–74. doi:10.1016/s0169-2046(02)00152-4.

Huang, S., X. Zhao, Y. Q. Sun, J. L. Ma, X. F. Gao, T. Xie, D. Xu, Y. Yu, and Y. C. Zhao. 2016. "Spatial Distribution of Organic Pollutants in Industrial Construction and Demolition Waste and their Mutual Interaction on an Abandoned Pesticide Manufacturing Plant." *Environmental Science-processes & Impacts* 18 (4): 482–492. doi:10.1039/c6em00019c.

Huang, S., X. Zhao, Y. Q. Sun, J. L. Ma, X. F. Gao, T. Xie, D. Xu, Y. Yu, and Y. C. Zhao. 2017. "Pollution of Hazardous Substances in Industrial Construction and Demolition Wastes and their Multi-path Risk Within an Abandoned Pesticide Manufacturing Plant." *Frontiers of Environmental Science & Engineering* 11 (1): 13. doi:10.1007/s11783-017-0901-2.

Iden, S. C., M. Delay, F. H. Frimmel, and W. Durner. 2008. "Assessing Contaminant Mobilization from Waste Materials: Application of Bayesian Parameter Estimation to Batch Extraction Tests at Varying Liquid-to-solid Ratios." *Environmental Science & Technology* 42 (10): 3717–3723. doi:10.1021/es702171z.

Jain, P., J. Powell, and T. Tolaymat. 2015. *Methodology to Estimate the Quantity, Composition, and Management of Construction and Demolition Debris in the United States*. Washington, DC: U.S. Environmental Protection Agency. EPA/600/R-15/111.

Jang, Y. C., and T. G. Townsend. 2001. "Occurrence of Organic Pollutants in Recovered Soil Fines from Construction and Demolition Waste." *Waste Management* 21 (8): 703–715. doi:10.1016/s0956-053x(01)00007-1.

Jung, J. S., S. H. Song, M. H. Jun, and S. S. Park. 2015. "A Comparison of Economic Feasibility and Emission of Carbon Dioxide for Two Recycling Processes." *KSCE Journal of Civil Engineering* 19 (5): 1248–1255. doi:10.1007/s12205-015-0708-2.

Kalbe, U., W. Berger, J. Eckardt, and F. G. Simon. 2008. "Evaluation of Leaching and Extraction Procedures for Soil and Waste." *Waste Management* 28 (6): 1027–1038. doi:10.1016/j.wasman.2007.03.008.

Kumar, R. 2017. "Influence of Recycled Coarse Aggregate Derived from Construction and Demolition Waste (CDW) on Abrasion Resistance of Pavement Concrete." *Construction and Building Materials* 142: 248–255. doi:10.1016/j.conbuildmat.2017.03.077.

Lee, J. Y., S. H. Moon, M. J. Yi, and S. T. Yun. 2008. "Groundwater Contamination with Petroleum Hydrocarbons, Chlorinated Solvents and High pH: Implications for Multiple Sources." *Quarterly Journal of Engineering Geology and Hydrogeology* 41: 35–47. doi:10.1144/1470-9236/07-021.

Li, J. R., Z. K. Ding, X. M. Mi, and J. Y. Wang. 2013. "A Model for Estimating Construction Waste Generation Index for Building Project in China." *Resources, Conservation and Recycling* 74: 20–26. doi:10.1016/j.resconrec.2013.02.015.

Li, J., M.-H. Wang, and Y.-S. Ho. 2011. "Trends in Research on Global Climate Change: A Science Citation Index Expanded-based Analysis." *Global and Planetary Change* 77 (1–2): 13–20.

Lu, W. S., X. Chen, D. C. W. Ho, and H. D. Wang. 2016. "Analysis of the Construction Waste Management Performance in Hong Kong: The Public and Private Sectors Compared Using Big Data." *Journal of Cleaner Production* 112: 521–531. doi:10.1016/j.jclepro.2015.06.106.

Lu, W., C. Webster, Y. Peng, X. Chen, and X. Zhang. 2017. "Estimating and Calibrating the Amount of Building-related Construction and Demolition Waste in Urban China." *International Journal of Construction Management* 17 (1): 13–24.

Lu, W. S., and H. P. Yuan. 2010. "Exploring Critical Success Factors for Waste Management in Construction Projects of China." *Resources, Conservation and Recycling* 55 (2): 201–208. doi:10.1016/j.resconrec.2010.09.010.

Lu, W., and H. Yuan. 2011. "A Framework for Understanding Waste Management Studies in Construction." *Waste Management* 31 (6): 1252–1260. doi:10.1016/j.wasman.2011.01.018.

Lu, W. S., H. P. Yuan, J. R. Li, J. J. L. Hao, X. M. Mi, and Z. K. Ding. 2011. "An Empirical Investigation of Construction and Demolition Waste Generation Rates in Shenzhen City, South China." *Waste Management* 31 (4): 680–687. doi:10.1016/j.wasman.2010.12.004.

Lye, C.-Q., R. K. Dhir, G. S. Ghataora, and H. Li. 2016. "Creep Strain of Recycled Aggregate Concrete." *Construction and Building Materials* 102: 244–259. doi:10.1016/j.conbuildmat.2015.10.181.

Malia, M., J. de Brito, M. D. Pinheiro, and M. Bravo. 2013. "Construction and Demolition Waste Indicators." *Waste Management & Research* 31 (3): 241–255. doi:10.1177/0734242x12471707.

Marzouk, M., and S. Azab. 2014. "Environmental and Economic Impact Assessment of Construction and Demolition Waste Disposal Using System Dynamics." *Resources, Conservation and Recycling* 82: 41–49. doi:10.1016/j.resconrec.2013.10.015.

Matias, D., J. de Brito, A. Rosa, and D. Pedro. 2013. "Mechanical Properties of Concrete Produced with Recycled Coarse Aggregates – Influence of the Use of Superplasticizers." *Construction and Building Materials* 44: 101–109. doi:10.1016/j.conbuildmat.2013.03.011.

Mercader-Moyano, P., and A. Ramirez-de-Arellano-Agudo. 2013. "Selective Classification and Quantification Model of C&D Waste from Material Resources Consumed in Residential Building Construction." *Waste Management & Research* 31 (5): 458–474. doi:10.1177/0734242x13477719.

Prell, C. 2012. *Social Network Analysis: History, Theory and Methodology*. Sage.

Pritchard, A. 1969. "Statistical Bibliography or Bibliometrics." *Journal of Documentation* 25 (4): 348–349.

Qiao, X. J., A. Kristoffersson, and T. B. Randrup. 2018. "Challenges to Implementing Urban Sustainable Stormwater Management from a Governance Perspective: A Literature Review." *Journal of Cleaner Production* 196: 943–952.

Rivero, A. J., R. Sathre, and J. G. Navarro. 2016. "Life Cycle Energy and Material Flow Implications of Gypsum Plasterboard Recycling in the European Union." *Resources, Conservation and Recycling* 108: 171–181. doi:10.1016/j.resconrec.2016.01.014.

Roussat, N., J. Mehu, M. Abdelghafour, and P. Brula. 2008. "Leaching Behaviour of Hazardous Demolition Waste." *Waste Management* 28 (11): 2032–2040. doi:10.1016/j.wasman.2007.10.019.

Scott, J. 2017. *Social Network Analysis*. London: Sage.

Shin, W. S., K. R. Na, and Y. K. Kim. 2016. "Adsorption of Metal Ions from Aqueous Solution by Recycled Aggregate: Estimation of Pretreatment Effect." *Desalination and Water Treatment* 57 (20): 9366–9374. doi:10.1080/19443994.2015.1029528.

Silva, R. V., J. de Brito, and R. K. Dhir. 2015a. "Comparative Analysis of Existing Prediction Models on the Creep Behaviour of Recycled Aggregate Concrete." *Engineering Structures* 100: 31–42. doi:10.1016/j.engstruct.2015.06.004.

Silva, R. V., J. de Brito, and R. K. Dhir. 2015b. "Tensile Strength Behaviour of Recycled Aggregate Concrete." *Construction and Building Materials* 83: 108–118. doi:10.1016/j.conbuildmat.2015.03.034.

Simion, I. M., C. Ghinea, S. G. Maxineasa, N. Taranu, A. Bonoli, and M. Gavrilescu. 2013. "Ecological Footprint Applied in the Assessment of Construction and Demolition Waste Integrated Management." *Environmental Engineering and Management Journal* 12 (4): 779–788.

Siva, V., I. Gremyr, B. Bergquist, R. Garvare, T. Zobel, and R. Isaksson. 2016. "The Support of Quality Management to Sustainable Development: A Literature Review." *Journal of Cleaner Production* 138: 148–157.

Tam, V. W. Y., D. Kotrayothar, and J. Z. Xiao. 2015. "Long-term Deformation Behaviour of Recycled Aggregate Concrete." *Construction and Building Materials* 100: 262–272. doi:10.1016/j.conbuildmat.2015.10.013.

Tam, V. W., and C. M. Tam. 2008. "Waste Reduction Through Incentives: A Case Study." *Building Research and Information* 36 (1): 37–43. doi:10.1080/09613210701417003.

Ulsen, C., H. Kahn, G. Hawlitschek, E. A. Masini, S. C. Angulo, and V. M. John. 2013. "Production of Recycled Sand from Construction and Demolition Waste." *Construction and Building Materials* 40: 1168–1173. doi:10.1016/j.conbuildmat.2012.02.004.

Van Praagh, M., and H. Modin. 2016. "Leaching of Chloride, Sulphate, Heavy Metals, Dissolved Organic Carbon and Phenolic Organic Pesticides from Contaminated Concrete." *Waste Management* 56: 352–358. doi:10.1016/j.wasman.2016.07.009.

van Raan, A. F. 2005. "For Your Citations Only? Hot Topics in Bibliometric Analysis." *Measurement: Interdisciplinary Research and Perspectives* 3 (1): 50–62.

Vegas, I., K. Broos, P. Nielsen, O. Lambertz, and A. Lisbona. 2015. "Upgrading the Quality of Mixed Recycled Aggregates from Construction and Demolition Waste by Using Near-infrared Sorting Technology." *Construction and Building Materials* 75: 121–128. doi:10.1016/j.conbuildmat.2014.09.109.

Wang, Y., N. Lai, J. Zuo, G. Chen, and H. Du. 2016. "Characteristics and Trends of Research on Waste-to-energy Incineration: A Bibliometric Analysis, 1999–2015." *Renewable and Sustainable Energy Reviews* 66: 95–104. doi:10.1016/j.rser.2016.07.006.

Wang, J. Y., Z. D. Li, and V. W. Y. Tam. 2014. "Critical Factors in Effective Construction Waste Minimization at the Design Stage: A Shenzhen Case Study, China." *Resources, Conservation and Recycling* 82: 1–7. doi:10.1016/j.resconrec.2013.11.003.

Wang, J., H. Wu, H. Duan, G. Zillante, J. Zuo, and H. Yuan. 2018. "Combining Life Cycle Assessment and Building Information Modelling to Account for Carbon Emission of Building Demolition Waste: A Case Study." *Journal of Cleaner Production* 172: 3154–3166.

Wang, J. Y., H. P. Yuan, X. P. Kang, and W. S. Lu. 2010. "Critical Success Factors for on-Site Sorting of Construction Waste: A China Study." *Resources, Conservation and Recycling* 54 (11): 931–936. doi:10.1016/j.resconrec.2010.01.012.

Wiedenhofer, D., J. K. Steinberger, N. Eisenmenger, and W. Haas. 2015. "Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25." *Journal of Industrial Ecology* 19 (4): 538–551. doi:10.1111/jiec.12216.

Won, J., J. C. P. Cheng, and G. Lee. 2016. "Quantification of Construction Waste Prevented by BIM-based Design Validation: Case Studies in South Korea." *Waste Management* 49: 170–180. doi:10.1016/j.wasman.2015.12.026.

Wu, H. Y., H. B. Duan, J. Y. Wang, T. Wang, and X. F. Wang. 2015. "Quantification of Carbon Emission of Construction Waste by Using Streamlined LCA: A Case Study of Shenzhen, China." *Journal of Material Cycles and Waste Management* 17 (4): 637–645. doi:10.1007/s10163-015-0404-9.

Wu, H. Y., H. B. Duan, L. N. Zheng, J. Y. Wang, Y. N. Niu, and G. M. Zhang. 2016a. "Demolition Waste Generation and Recycling Potentials in a Rapidly Developing Flagship Megacity of South China: Prospective Scenarios and Implications." *Construction and Building Materials* 113: 1007–1016. doi:10.1016/j.conbuildmat.2016.03.130.

Wu, H. Y., J. Y. Wang, H. B. Duan, L. Ouyang, W. K. Huang, and J. Zuo. 2016b. "An Innovative Approach to Managing Demolition Waste via GIS (Geographic Information System): A Case Study in Shenzhen City, China." *Journal of Cleaner Production* 112: 494–503. doi:10.1016/j.jclepro.2015.08.096.

Wu, Z., A. T. W. Yu, L. Shen, and G. Liu. 2014. "Quantifying Construction and Demolition Waste: An Analytical Review." *Waste Management* 34 (9): 1683–1692. doi:10.1016/j.wasman.2014.05.010.

Xuan, D. X., A. A. A. Molenaar, and L. J. M. Houben. 2016. "Shrinkage Cracking of Cement Treated Demolition Waste as a Road Base." *Materials and Structures* 49 (1-2): 631–640. doi:10.1617/s11527-015-0524-7.

Younis, K. H., and K. Pilakoutas. 2013. "Strength Prediction Model and Methods for Improving Recycled Aggregate Concrete." *Construction and Building Materials* 49: 688–701. doi:10.1016/j.conbuildmat.2013.09.003.

Yuan, H., and L. Shen. 2011. "Trend of the Research on Construction and Demolition Waste Management." *Waste Management* 31 (4): 670–679. doi:10.1016/j.wasman.2010.10.030.

Zega, C. J., Y. A. Villagran-Zaccardi, and A. A. Di Maio. 2010. "Effect of Natural Coarse Aggregate Type on the Physical and Mechanical Properties of Recycled Coarse Aggregates." *Materials and Structures* 43 (1–2): 195–202. doi:10.1617/s11527-009-9480-4.

Zhao, W., R. B. Leeftink, and V. S. Rotter. 2010. "Evaluation of the Economic Feasibility for the Recycling of Construction and Demolition Waste in China-the Case of Chongqing." *Resources, Conservation and Recycling* 54 (6): 377–389. doi:10.1016/j.resconrec.2009.09.003.

Zheng, L. N., H. Y. Wu, H. Zhang, H. B. Duan, J. Y. Wang, W. P. Jiang, and Q. B. Song. 2017. "Characterizing the Generation and Flows of Construction and Demolition Waste in China." *Construction and Building Materials* 136: 405–413. doi:10.1016/j.conbuildmat.2017.01.055.