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LIFE CYCLE ASSESSMENT OF RECYCLED CONSTRUCTION MATERIALS: METHODOLOGY FRAMEWORK DEVELOPMENT AND RESULTS EVALUATION

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Life Cycle Assessment of Recycled Construction Materials: Methodology Framework Development and Results Evaluation

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ABSTRACT

The demand for green construction materials and products is burgeoning globally due to the shortage of natural materials and the associated environmental consequences. In addition, the sustainable management of rapidly increasing waste materials in Hong Kong is urgent due to the shortage of and the associated environmental burdens on landfills. With the promotion of environmental protection in the construction industry, the mission to achieve more sustainable use of resources during the production process of construction materials/products is becoming increasingly important. In this study, the environmental evaluation of valorized waste materials and their utilizations were evaluated using life cycle assessment (LCA) techniques, with the aim to identify a resource-efficient solution for waste materials as well as construction sustainability.

LCA, a holistic approach for evaluating the environmental impacts of a product or system, was adopted in this study. In order to select sustainable aggregates, a comparative environmental consequence of recycled aggregates production from construction and demolition (C&D) waste and waste glass, and natural aggregate production from virgin materials was assessed using LCA approach. Environmental performance of concrete paving and partition wall blocks prepared with natural and recycled materials were also evaluated by LCA. Environmental impacts of different types of cement produced in Hong Kong were assessed based on their strength class, and several potential sustainable strategies were proposed for impacts reduction.

To promote sustainability in the concrete industry, various supplementary cementitious materials (SCMs), such as fly ash, blast furnace slag and silica fume, have been used to replace cement in the production of concrete. The nature of these waste materials has been changed from wastes to by-products according to international conventions. As such, their environmental impacts are required to be reallocated consequently in LCA. However, the choice of the impacts distribution procedure for LCA of concrete incorporating SCMs is a methodological challenge. This study critically evaluated different approaches with a case study on concrete production in Hong Kong. Based on the findings, a decision matrix was provided to select the most suitable approach which can ensure appropriate allocation approaches of the by-products.

The assessment of social sustainability has seldom been carried out during the selection of materials due to the lack of available social life cycle assessment (S-LCA) tools. This study developed a new single score based methodology, namely a social sustainability grading model, for assessing the social sustainability performance of construction materials. A case study on construction materials was conducted to illustrate the implementation of the method using case-specific first-hand data.

On the basis of the collected data, assumptions made and the defined system boundaries, the findings of the study showed the use of recycled aggregates reduced 49-59% of total environmental loads when compared that of natural aggregates. The results also demonstrated that eco-blocks consumed 26-32% lower energy, and emitted 17-20% lower greenhouse gases compared to the natural blocks. In addition, concrete partition wall blocks prepared with concrete slurry waste and recycled aggregates achieved higher sustainability than the conventional ones.

The LCA results demonstrated that ordinary Portland cement production had high environmental impacts as a result of the use of associated raw materials and burning of fossil fuels. Significant environmental impact reductions associated with cement production can be achieved by the use of glass powders as part of the raw materials to substitute clinker, and bio-fuel produced from wood wastes as a co-fuel with coal.

The system expansion can be the preferred approach over allocations for assessing the environmental impacts of concrete/concrete products produced with SCMs. Based on the proposed S-LCA method and sustainability index for conducting S-LCA, recycled aggregates from waste materials scored higher (about 31-34%) social sustainability scores than the imported natural aggregates. In addition, recycled aggregates and natural aggregates achieved 'sustainable' and 'neutral' rating sustainability levels, respectively.

The results of this research can be used as a guideline for sustainable waste management and resourceful utilization of wastes, a basis for the selection of sustainable construction materials, a means of a comprehensive environmental and social sustainability assessment of construction materials and products, as well as a reference to improve the sustainability performance in the construction industry.

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AusLCI	The Australian National Life Cycle Inventory Database
BECL	Business Environment Council Limited
BS	British Standards
C&D	Construction and Demolition
CCANZ	Cement and Concrete Association of New Zealand
CLCD	The Chinese Life Cycle Database
CLP	The China Light and Power
CML	Center of Environmental Science
CO_2 eq	Carbon Dioxide Equivalent
CPM	Centre for Environmental Assessment of Product and Material Systems
CRF	Carbon Reduction Factor (CO_2 eq)
CS	Crushed Stone
CSACWUTI	China's Strategic Alliance of Construction Waste Utilization Technology Innovation
CSW	Concrete Slurry Waste
CWM	Construction Waste Management
DALY	Disability-Adjusted Life Years
DEFRA	Department for Environment, Food and Rural Affairs
EB	Eco Paving Block
Eco-GC	Eco-Glass Cement
EDIP	Environmental Development of Industrial Products
EFCA	European Federation of Concrete Admixtures
E-LCA	Environmental Life Cycle Assessment
ELCD	European Reference Life Cycle Database
EPA	The U.S. Environmental Protection Agency
ESF	Energy Saving Factor
ETWB	Environment, Transport and Works Bureau
EU	European Union
FA	Fly Ash
FRCA	Fine Recycled Concrete Aggregate
FU	Functional Unit
G	Generation
GBFS	Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GIC	Green Island Cement
GRI	Global Reporting Initiatives
GWP	Global Warming Potential
HKEB	Hong Kong Environment Bureau
HKEPD	Hong Kong Environmental Protection Department
HKGPC	Hong Kong Green Purchasing Chapter
IEA	International Energy Agency
IMPACT 2002	IMPact Assessment of Chemical Toxics, version 2002
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization For Standardization
JRC	Joint Research Centre

kg	Kilogram
LC	Limestone Cement
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LIME	Life-cycle Impact Assessment (LCIA) Method based on Endpoint modeling
MD	Mix-design
MJ	Mega Joule
MP	Manufacturing Process
MPA	Mineral Products Association
mPt	Milli-points
MSW	Municipal Solid Waste
NENT	North East New Territories
NO_x	Nitrogen Oxides
OPC	Ordinary Portland Cement
PDF	Potentially Disappeared Fraction of Species
PFC	Portland Fly Ash Cement
RS	River Sand
RTS	Refuse Transfer Stations
SCMs	Supplementary Cementitious Materials
SENT	South East New Territories
SETAC	Society of Environmental Toxicology and Chemistry
SF	Silica Fume
S-LCA	Social Life Cycle Assessment
SOC	Sumitomo Osaka Cement
SSG	Social Sustainability Grading
SSS	Score of the Social Sustainability
t	Tonne
TiO_2	Titanium Dioxide
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
UNEP	United Nation Environment Programme
USLCI	The U.S. Life Cycle Inventory
VCS	Voluntary Carbon Standard
WB	World Bank
WBCSD	World Business Council for Sustainable Development
WCA	World Construction Aggregates
WENT	West New Territories
WG	Waste Glass
y	Year

CHAPTER 1

INTRODUCTION

1.1 Background

The construction industry is a major source of environmental consequences and contributes significantly to natural resource depletion (Bribian et al. 2011). About 3 billion metric tonnes of raw materials are used annually for the manufacturing of construction materials worldwide (Saghafi and Teshnizi 2011). The construction industry uses approximately 50% of the earth's natural resources and produces 50% of its waste (De Schepper et al. 2014).

Nowadays, environmental protection and sustainability are becoming important issues globally. With special attention to sustainable development, the construction industry is playing an important role in achieving sustainability through the application of various sustainability tools that assess the impacts of the whole life cycle of usage (materials, products and processes), minimize waste generation, ensure energy efficiency, and reuse of recycled materials in construction (Koroneos and Dompros 2007). In order to investigate a quantitative analysis of environmental impacts of construction materials and products, as well as recycled materials from wastes, a holistic analytical approach, such as a life cycle assessment (LCA), is required. As a well-established technique specified in international standards (ISO 2006a,b), LCA has been extensively used to evaluate environmental impacts and serve as a decision support tool in both business and political sectors (Dong et al. 2015).

Aggregates are considered as one of the basic construction materials. However, the quarrying activities for natural aggregates production are responsible for significant environmental consequences and natural resources depletion. Due to the increases in urban populations and the boom of construction activities throughout the world, a huge amount of construction and demolition (C&D) wastes are being generated along with other municipal solid wastes, such as post consumer waste glasses. Therefore, an effective management of these wastes is becoming particularly imperative to resource-scarce and compact cities, like Hong Kong, as improper management may impose considerable environmental damages. In addition, the construction industry needs alternative and sustainable sources of aggregates, as a shortage of natural aggregates has emerged worldwide. Hence, the need to study the effective management of construction wastes, and their potential to produce recycled aggregates and utilizations, is burgeoning globally.

Recycling of several waste materials to produce recycled aggregates can be considered as a valuable option, not only in order to minimize landfill impacts but also to reduce usage of natural resources. Numerous studies have demonstrated that recycled aggregates from construction and demolition (C&D) waste can be used as construction materials (Jullien et al. 2012; Gayarre et al. 2013). In addition, recycled waste glass is also considered to be a potential aggregate source. Several studies have demonstrated the successful utilization of waste materials in producing different types of eco-products. In Hong Kong, concrete paving blocks have been developed with recycled C&D waste and waste glass, substituting a significant amount of natural materials. In addition, concrete slurry waste (CSW) can potentially be recycled for use as recycled aggregates or as cementitious binder for producing eco-products.

Cement, the most commonly used construction material in the world, has garnered broad and special attention, especially due to its high greenhouses gas (GHGs) emissions and high energy consumption (Mikulcic et al. 2016). In order to select low impact cement, a comprehensive evaluation on the environmental impacts of different types of cement manufactured in Hong Kong is necessary. In addition, sustainable solutions for the reduction of environmental impacts in the cement industry are particularly important.

Concrete is one of the most commonly used construction materials. Due to increasing sustainability concerns in the construction sector and the initiatives to produce more durable concrete, it has been a common practice to produce concrete with cement replacements using the so-called supplementary cementitious materials (SCMs). The most commonly used SCMs are fly ash (FA), granulated blast furnace slag (GBFS) and silica fume (SF). However, their status has been changed from wastes to by-products or co-products and their environmental impact should then be accounted for and allocated to by-products in LCA (Chen et al. 2010b).

However, the choice of environmental impact distribution approaches in LCAs of concrete incorporating SCMs is a methodological challenge and one of the unsolved issues in LCAs. Therefore, a sound methodological guideline is necessary for SCMs used in construction.

Sustainability assessments that quantify social impacts are a new research dimension in LCA of materials/products/processes. However, the social sustainability assessment has seldom been carried out during the construction materials selection process due to the lack of a social life cycle assessment (S-LCA) tool. S-LCA can be used as a complement to the environmental life cycle assessment, which is essential to increase the understanding of sustainability comprehensively in the construction industry, and to select more sustainable construction materials.

This dissertation presents a comprehensive roadmap for improving several wastes management approaches and utilizations in eco-products, producing cleaner construction materials, and selecting sustainable options for the decision makers, stakeholders, manufacturers, researchers and other parties who are interested in lowering the environmental burdens associated with these materials/products. In addition, the guidelines for selecting the appropriate environmental impacts distribution method for assessing the concrete or concrete products with SCMs are presented. Finally, an innovative method for assessing the social sustainability performance of construction materials proposed in this thesis will provide a basis for social sustainability assessment of various materials. The method can capture important aspects of sustainability, one of the three pillars of sustainable development, which can be used as a complement to environmental life cycle assessment used for the decision-making processes, and strategic design and improvements.

1.2 Aim and objectives

The study aims to identify the potential sustainable solutions to turn waste materials, including C&D waste, CSW, waste glass and wood waste derived from construction activities, into the value added eco-products in Hong Kong using LCA techniques. This is followed by proposing an advanced and innovative method for assessing social sustainability performance of construction materials. The study focuses on five specific objectives:

- To compare the environmental impacts of recycled aggregates derived from C&D waste and waste glass with natural imported aggregates in Hong Kong.
- To assess the environmental performance of recycled construction products (e.g. recycled and natural paving blocks and partition wall blocks) in Hong Kong using the LCA approach.
- To evaluate the environmental impacts of different types of cement production in Hong Kong based on strength class, and then proposed potential and sustainable strategies for reducing environmental impacts in the cement industry in Hong Kong.
- To provide an optimized basis for the selection of environmental impacts distribution approach for cement, concrete and concrete products assessment when SCMs are involved.
- To establish a ‘social sustainability grading’ model, a S-LCA method for assessing social sustainability performance of construction materials.

1.3 Scope of the study

The scope of the study can be broadly divided into two parts (Figure 1-1). The first part includes the application of LCA techniques in the assessment of environmental impacts of several waste management approaches (e.g. C&D waste, wood waste, CSW and waste glass) and utilization in producing recycled materials and products. Investigations in the second part include the methodology development and the selection of environmental impacts assessment methods in the construction industry. Investigations conducted in this study are described in the introduction sections of Chapters 3-8.

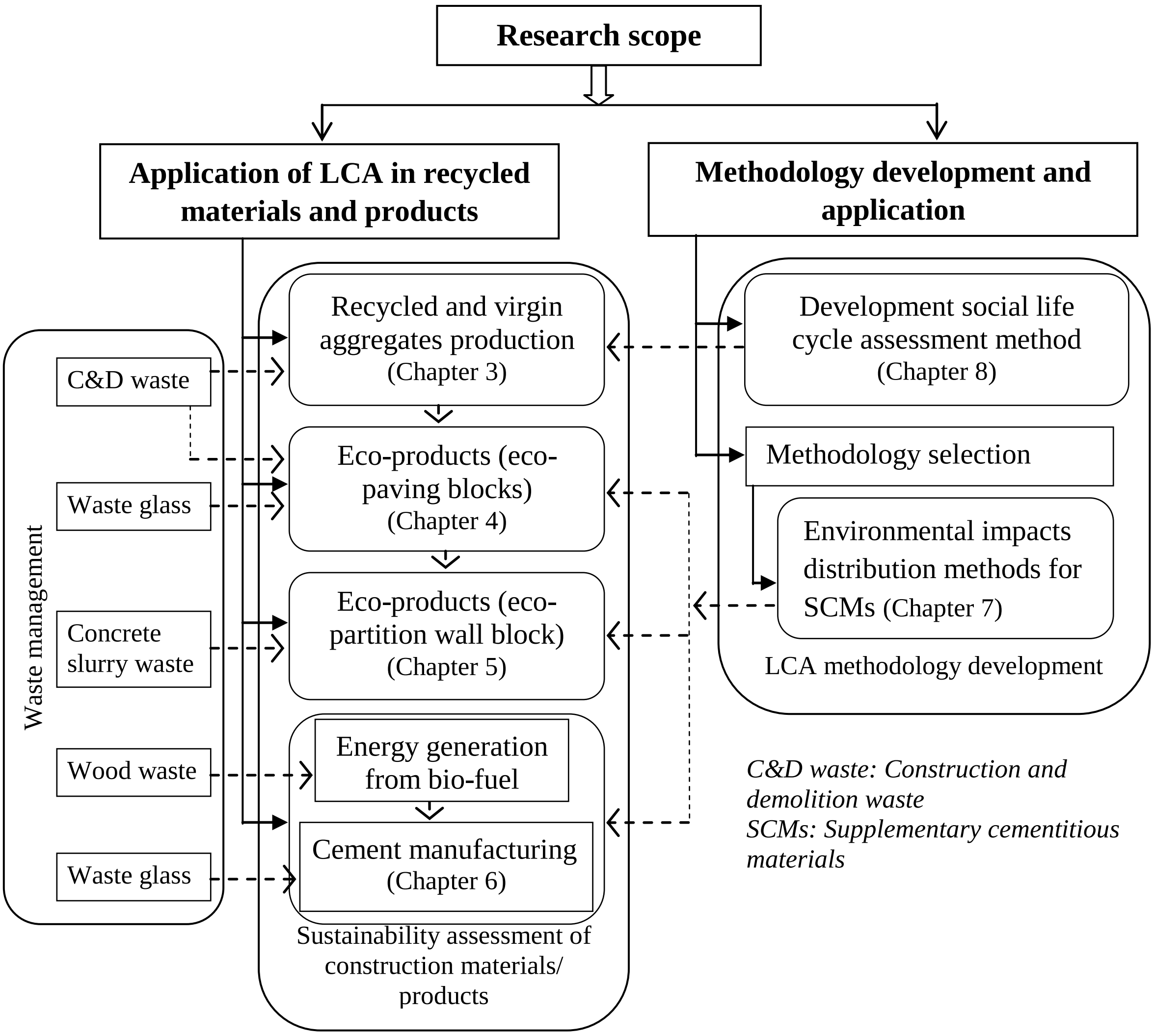


Figure 1-1 - Scope of the research

In this chapter, the background and motivation, objectives and scope of the study are provided.

In Chapter 2, a review of the literature, providing a brief overview of the studied waste materials, their management and recycling for value-added products is given. The implementation of E-LCA and S-LCA in the construction industry is further discussed, and the drawbacks of the reviewed studies are highlighted and the research needs are pointed out. In addition, detailed information regarding the research procedures and the selection of the methodology in the study is discussed. The definition, framework and methods of E-LCA and S-LCA are elaborated. The impacts quantification methods and tools, and databases are also introduced. Sufficient details are provided to describe the basic concept of LCA, and to show the originality and reliability of this study.

In Chapter 3, the comparative environmental performance of different aggregates derived from recycled materials and virgin sources in Hong Kong is presented. The details of C&D waste and waste glass management, and aggregates production system are described. The contributions of environmental impacts from different sub-processes are also discussed. In addition, a sensitivity analysis is carried out to verify the results.

In Chapter 4, the environmental friendliness of concrete paving blocks prepared with recycled materials (i.e. recycled aggregates and fly ash), and natural materials (e.g. natural aggregates and ordinary Portland cement) are assessed. The contributions of impacts from different materials are highlighted. Sensitivity analysis based on the variation of key input parameters and transport distance is also carried out.

In Chapter 5, a basis for sustainable management and utilization of concrete slurry waste (CSW) is provided. Different management scenarios are critically evaluated using LCA. Under the best scenario, fresh CSW is then utilized in the production of concrete partition wall blocks by incorporating recycled aggregates. The findings are compared with the conventional partition wall blocks to establish a basis for managing and reusing CSW sustainably.

In Chapter 6, the environmental impacts of different types of cement production in Hong Kong are assessed and compared. The sustainable strategies for the reduction of environmental impacts using locally available waste materials in the cement industry are presented.

In Chapter 7, a methodological rigor for the selection of impact distribution methods of cement/concrete/concrete products due to the allocation of SCMs is presented by critically evaluating different approaches. A guideline and decision matrix is provided with a case study to corroborate the results.

In Chapter 8, a comprehensive social life cycle assessment methodology for assessing the social sustainability performance of construction materials is developed. A single score based the S-LCA method is presented, and a case study is conducted to validate the method. In this method, new category and sub-categories are proposed, hotspot of sub-categories are integrated, comprehensive and step-by-step data collection is introduced, impact calculation hierarchy and equations are developed, indicators benchmarking and scoring systems are established, and a social sustainability grading scale is proposed.

In Chapter 9, the findings of this study are summarized. The contributions of the study are highlighted, and the potential works for future study are suggested.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a brief review of the previous studies and techniques on environmental sustainability assessment of recycled construction materials, green products, cement and concrete manufacturing using life cycle assessment (LCA) techniques. LCA, a well-established technique specified in international standards (ISO 2006a,b), has been extensively used to evaluate environmental impacts and serves as a decision support tool (Dong 2014). Following the review, studies are evaluated to discuss major outcomes and existing gaps in the research arena. Details and critical review are presented at each individual perspective from Chapter 3 to Chapter 8.

The reviewed literature was selected from peer-reviewed publications and reports that follow systematic LCA guidelines, provided by ISO 14040 framework (ISO 2006a). The review consists of three segments of studies: the first group covers LCA studies related to the management of construction wastes (such as C&D waste, concrete slurry waste and wood wastes) and waste glass. The second group is a compilation of LCAs regarding construction materials (e.g. aggregates and cement) and construction products. Finally, the third group reviews LCA studies focused on social life cycle assessments in the construction industry.

2.2 LCA of waste management (C&D waste, waste glass and wood waste)

In recent years, there has been increasing development and application of LCA within the field of waste management to support environmentally sound decisions in different countries. Initially, LCA has been developed for the assessment of various products which typically include the processing of material extraction, transport, manufacturing, use and end-of-life of the products. Then, LCA has been rapidly adapted to various systems and waste management systems (Clavreul et al. 2013; Mercante et al. 2012).

2.2.1 Construction and demolition waste

Construction and demolition (C&D) waste is one of the major waste types in modern society, and its management is a serious concern throughout the world (Butera et al. 2015). A substantial amount of C&D wastes are generated due to the boom of construction, renovation, demolition and civil works (e.g. infrastructure projects) worldwide. For example, over 1.5 billion tonnes of C&D wastes were generated only in China in 2014 (CSACWUTI 2015), about 45 million tonnes (MT) in Spain in 2008 (Gangolells et al. 2014), 100 MT in UK in 2012 (DEFRA 2015), 890 MT in EU (Saez et al. 2014), 18 MT in Australia in 2010-11 (Randell et al. 2014), 500 MT in USA in 2013 (EPA 2015), and 23 MT in Hong Kong in 2013 (HKEPD 2015). Hence, tremendous pressure has been placed on many large cities in developing and developed countries/regions to implement sustainable construction waste management practices (Li et al. 2016c).

Up to date, several LCA studies have been conducted on sustainable management of C&D waste. Blengini et al. (2009) assessed the environmental sustainability of recycling potential and landfilling of C&D waste in Italy. The study found a very high recycling potential of C&D from an environmental and economic point of view. Mercante et al. (2012) conducted a detailed study on C&D wastes recycling and landfilling in Spain. A similar study was conducted in the USA by Kucukvar et al. (2009). Butera et al. (2015) assessed the environmental performance of C&D waste by comparing landfill disposal and recycled aggregates to substitute natural aggregates in road base utilization in Denmark. The study found that the utilization as road base materials was a preferable option over the landfill disposal. Kucukvar et al. (2016) conducted a hybrid LCA to quantify the total environmental impacts of various C&D waste management options, such as recycling, landfilling and incineration. An economically and environmentally sound benefit was observed when recycling various materials from C&D waste in the USA.

Most LCA studies focused on C&D waste management demonstrated the recycling and reuse strategy has advantages over traditional landfill disposal with respect to potential environmental savings. However, the environmental performance and magnitude of environmental savings varied significantly amongst different studies. This is due to the differences in geographical location, waste management systems, data quality, energy mix, consideration of end-of-life scenarios, fuel considerations, processes, as well as system boundaries. Therefore, local and case-specific studies with detailed inventory analysis are needed for effective C&D waste management decision making processes.

In Hong Kong, a significant amount of C&D waste is generated each year, and most of them are disposed of at public fills (where inert materials, such as sand, bricks and concrete deposited for use as a land reclamation) and some of them are sent to landfills (where non-inert and mixed materials, such as bamboo, plastics, wood waste, paper, vegetation, etc. are disposed) for disposal (Figure 2-1).

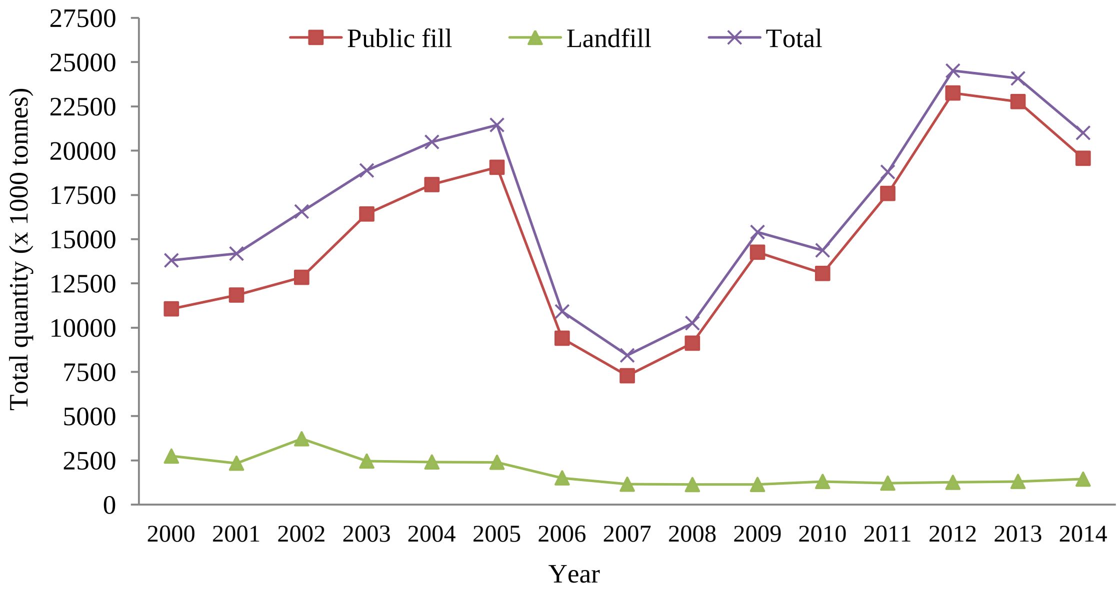


Figure 2-1 - C&D waste management in Hong Kong (Source: HKEPD 2015)

It is well known that mineral waste from C&D activities has a high potential to be used as recycled aggregates. However, the share of recycled aggregates compared to the total aggregate demand in Hong Kong was very low (about 0.3%) (Gan et al. 2016). Therefore, a comprehensive study on the assessment of environmental sustainability of recycled aggregates production from C&D waste is necessary to promote its recycling and reuse. In addition, a material to material comparison is important to help the construction industry in choosing sustainable materials to minimize environmental damages, and sustainable management of waste and efficient natural resource utilization.

2.2.2 Waste glass

A considerable amount of post consumer waste glass is disposed of Hong Kong landfills annually (Figure 2-2). The recycling rate of waste glass in Hong Kong was less than 20%, which is very low when compared to other countries, such as Germany (90%), UK (44%), Japan (95%), South Korea (70%) and Taiwan (84%) (HKEPD 2015). This is due to the lack of a glass manufacturing industry in Hong Kong.

Several experimental studies have been conducted to assess the potential use of waste glass as aggregates in various forms of construction materials, such as fine aggregates in cement mortar and concrete products (Ling et al. 2013; Ling and Poon 2012). However, until now, no studies have attempted to assess the environmental impacts for producing recycled aggregates from waste glass using LCA.

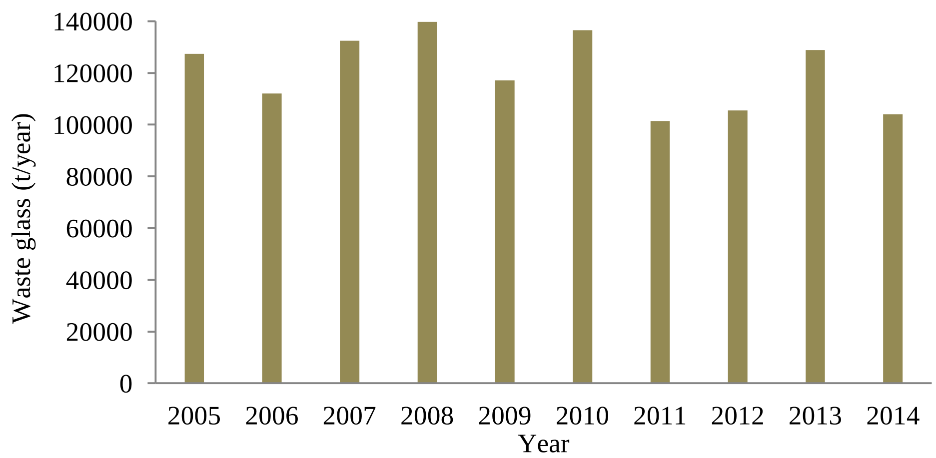


Figure 2-2 - Waste glass landfilled in Hong Kong (Source: HKEPD 2015)

2.2.3 Wood waste

A significant amount of wood wastes generated from C&D activities and other sources are landfilled in Hong Kong each year (Figure 2-3). This is due to the lack of recycled wood product manufacturers and economic barriers to export the wastes. However, bio-fuel (e.g. wood pellets) derived from wood waste is a burgeoning technology since it can provide an alternative to burning fossil fuels and environmental concerns of burning fossil fuels (Zhang et al. 2010). Wood pellets can be burned directly as a heating fuel or be used as co-fuel with coal (Magelli et al. 2009). Only a few LCA studies have been conducted on wood pellet production and the assessment of their application for energy generation in North America and in Europe (Giuntoli et al. 2015; Katers et. al. 2012; Zhang et al. 2010).

Most studies have focused on wood wastes from fresh wood residues due to the environmental concern and regulations of wood waste from C&D waste composition. Wood wastes generated from C&D activities and other wood product wastes can be a good potential source of renewable energy. In order to assess the technical feasibility of wood pellet production and application in the energy intensive industry, the physical and chemical analysis of the wood waste is necessary along with environmental feasibility assessment by LCA. To produce greener fuels in comparison to coal for energy generation, and then potential applications (for example in the cement industry to substitute coal), an integrated assessment is required to assess the technical feasibility and environmental sustainability of wood waste derived from the C&D waste stream.

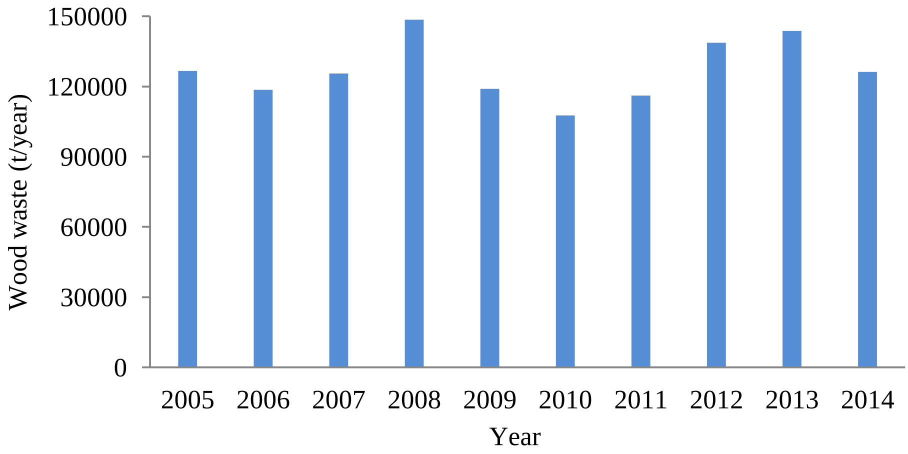


Figure 2-3 - Wood waste landfilled in Hong Kong (Source: HKEPD 2015)

2.3 LCA of construction materials and products

The construction industry uses a considerable amount of raw materials, which contributes to the depletion of natural resources and negative environmental impacts (Bribian et al. 2011). Environmental management associated with emissions play a leading role in the sustainable development of the construction industry in this century (Wu et al. 2014a). This section provides a brief overview of LCA studies on essential construction materials and products.

2.3.1 Aggregates

Aggregates are considered as one of the most widely used construction materials in the world (Gan et al. 2016). About 9 billion tonnes of natural aggregates are extracted from nature and used every year (Mehta 2002). The global market for construction aggregates is expected to increase 5.2 percent per year (about 48.3 billion metric tonnes in 2015), in which China alone accounts for about half of the new aggregates demand (WCA 2016). Their extraction, processing, handling and uses account for about 7% of total global energy consumption. In addition, transportation of primary minerals alone is responsible for 40% of the total energy consumption by the industry (Mankelow et al. 2010; Vieira 2007; Lippiatt 2007).

Several LCA studies are available for sustainable manufacturing and supply of aggregates in different countries. For example, studies in this regard have been conducted by Jullien et al. (2012) in France, Estanqueiro (2011) in Portugal, Simion et al. (2013) in Romania, and Blengini et al. (2007) in Italy. However, few studies are available on recycled aggregates production from C&D waste, including those by Simion et al. (2013) in Romania, Blengini and Garbarino (2010) in Italy, Butera et al. (2015) in Denmark, and Mercante et al. (2012) in Spain.

In Hong Kong, the demand for aggregates is about 14.66 million tonnes per year (Gan et al. 2016). The supply of aggregates is associated with high environmental impacts, as Hong Kong relies heavily on imported aggregates. In addition, Hong Kong urgently needs to seek alternative sources of aggregates, as the local quarry sites for the aggregate production are expected to be exhausted soon.

To ensure sustainable production of natural aggregates and effective management of C&D waste, LCA is a well known tool for measuring and comparing environmental impacts quantitatively. For example, Gan et al. (2016) has employed LCA for multi-objectives evaluation of aggregates supply in Hong Kong. However, detailed inventory, recycling benefits and consequences of alternative scenarios were not evaluated in this study. It has already been mentioned that C&D waste and waste glass are potentially good sources for the production of recycled aggregates in Hong Kong, which also ensures sustainable management of waste materials. Therefore, a case-specific, detailed and comparative LCA study on natural and recycled aggregates production and supply is necessary in order to ensure sustainability in construction, as well as effective waste management in Hong Kong.

2.3.2 Cement

Cement is one of the most commonly used (and energy and emissions intensive) construction materials. To achieve environmental sustainability, the reduction of environmental impacts in the cement industry has gained increasing attention worldwide. Cement production contributes to 5-10% of the total GHGs emissions (Scrivener and Kirkpatrick 2008) and 12-15% of total industrial energy use worldwide (Madlool et al. 2011).

Hong Kong consumes a considerable amount of cement each year due to its high demand for construction activities. However, cement manufacturing in Hong Kong is associated with high environmental pollution. For example, in Hong Kong, the carbon emission factor for Ordinary Portland cement production is 1.006 kg CO_2 eq/kg (Zhang et al. 2014). This is due to the transport of raw materials and fossil fuel combustion throughout the manufacturing process.

Various strategies have been taken to improve the cement production process in different countries, such as the use of alternative fuels, materials, modifications of manufacturing process, etc (Habert et al. 2010; Strazza et al. 2011; Moya et al. 2011).

To improve the environmental performance of the cement industry, innovative and sustainable strategies are not only important but also in urgent need. The use of alternative materials, such as the use of glass powders from locally generated waste glass bottles as part of the raw materials, and the use of bio-fuel produced from locally generated wood wastes as a co-fuel with coal, can be sustainable solutions to achieve cleaner cement production in Hong Kong. In addition, a comprehensive assessment of the environmental impacts of different types of cement manufactured in Hong Kong based on strength class is necessary for selecting low-impact cement.

2.3.3 Concrete/concrete products

The production of concrete has been recognized to lead to major environmental impacts. Its annual consumption rate is around 25 gigatonnes globally (over 3.5 tonnes per capita) (Gursel et al. 2014). Currently, global concrete manufacturing accounts for more than 5%, and about 2.1 billion tonnes of anthropogenic GHGs emissions annually (IEA/WBCSD 2009). Increasingly, LCA techniques have been adopted in the concrete industry to identify and minimize its environmental impacts. For example, Zhang et al. (2014) assessed the carbon footprint of conventional concrete using LCA in Hong Kong. Turk et al. (2015) assessed the environmental performance of conventional concrete and green concrete prepared by foundry sand and steel slag using LCA. Carbon emission of conventional concrete and concrete made with high volume fly ash and pulverized limestone was assessed by Celik et al. (2015). Most of the studies have concluded that emissions can be minimized by using alternative materials.

The demand for green construction materials and eco-products is burgeoning globally due to the shortage of natural materials and the relevant environmental consequences of natural materials. However, only a few studies have focused on the environmental performance of recycled products prepared with the mentioned waste materials using LCA techniques. For example, Gayarre et al. (2016) assessed concrete kerbs prepared by replacing a certain amount of natural sand with recycled sand from C&D waste. However, the environmental performance of the use of other recycled aggregates, such as coarse aggregates from C&D waste and fine aggregates from waste glass in concrete products have yet to be investigated.

Concrete paving blocks with recycled materials (e.g. C&D waste and waste glass) have been developed in Hong Kong. Therefore, the environmental impacts and sustainability associated with the paving blocks manufactured with virgin materials and recycled materials by LCA techniques need to be explored to provide a sound environmental profile for the promotion of recycled products.

Concrete slurry waste (CSW) is deposited in sedimentation tanks after washing out over-ordered/rejected fresh concrete from concrete trucks in concrete batching plants. A few recycling strategies of CSW have been proposed, such as using CSW as recycled aggregates, filler material and as slurry-based geo-polymer (Zervaki et al. 2013; Kou et al. 2012b; Yang et al. 2009). These studies concluded that the use of CSW as aggregate, geopolymer concrete and filler materials in concrete are mechanically feasible. However, till now, no LCA study has been conducted to assess the environmental sustainability of various CSW management strategies and utilization in construction products. Therefore, the environmental evaluation of different CSW management strategies and their utilization for the production of partition wall blocks by the LCA technique is necessary.

2.4 Social sustainability of construction materials

Social sustainability assessment is considered to be one of the three pillars of sustainability assessment. Social life cycle assessment (S-LCA) is recognized as a powerful tool for assessing the social impacts and related sustainability of a product or material (Benoît and Mazijn 2009). According to Hosseinijou et al. (2014), the selection of a material should not only be based on its functional performance but should also consider its environmental, economic and social performance throughout its whole life cycle. It has already been mentioned that a number of studies have focused on the environmental evaluation of construction materials using the LCA approach. There is a need to assess the social performance of construction materials, not only to address the social impacts in sustainable material selection but also to identify the potential circumstances to improve the social conditions of affected stakeholders (Benoit et al. 2010; Petersen 2013). However, the social consequences of construction materials have been seldom reported. This is due to the lack of a social sustainability assessment tool for assessing the social sustainability of construction materials. A comprehensive S-LCA methodology for recycled construction materials /products has yet to be developed, and a case study regarding the social impacts of essential construction materials has yet to be conducted.

2.5 Research methodology

2.5.1 Environmental life cycle assessment

The concept 'life cycle assessment (LCA)' is one of the recognized environmental management tools. LCA is a 'cradle-to-grave' approach beginning with the collecting of raw materials from the earth to create the product and ending at the point (e.g. whole life cycle) when all materials are returned to the earth (EPA 2006).

According to the International Organization for Standardization (ISO), environmental life cycle assessment (E-LCA) deals with the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life management, recycling and final disposal (ISO 2006b). It is considered to be an effective, systematic and quantitative decision support tool to evaluate the environmental burdens of a product/process, and to evaluate alternatives for environmental improvements (ISO 2006a; Curran 2012; Manfredi et al. 2011).

According to ISO 14044 (2006a), E-LCA can effectively assist in

- *identifying opportunities to improve the environmental performance of products at various points in their life cycle,*
- *informing decision makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),*
- *the selection of relevant indicators of environmental performance, including measurement techniques, and*
- *marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).*

2.5.1.1 Framework of E-LCA

The principle and framework for conducting environmental LCA has been provided by the ISO in its guidelines '*ISO-14040: Environmental Management–Life Cycle Assessment–Principles and Framework* (ISO 2006a)' (Figure 2-4).

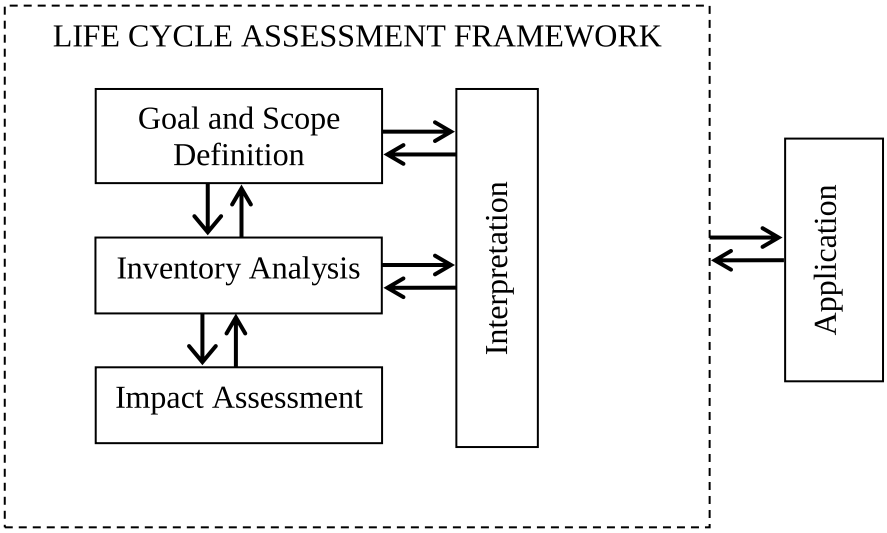


Figure 2-4 - Life cycle assessment framework (ISO 2006a)

❖ ***Goal and scope definition*** – The first step of LCA is goal and scope definition which includes defining the reasons for conducting the study, defining and describing the product, process or activity, establishing the context in which the assessment is to be carried out and identifying the system boundaries, functional unit, assumptions, impact assessment methodology and environmental impact categories, etc.

❖ ***Life cycle inventory analysis*** – The second step is life cycle inventory analysis (LCI) which includes data collection and calculation procedures to quantify relevant inputs and outputs of a product or process system. In LCI, data should be energy inputs, raw material inputs, ancillary inputs, other physical inputs, products, co-products and waste, releases into the air, water and soil, and other environmental aspects which should be collected within the system boundary and goal of the study. The collected data are utilized to quantify the inputs and outputs of a unit process (ISO 2006b).

❖ ***Life cycle impact assessment*** – The life cycle impact assessment (LCIA) step aims to evaluate the magnitude and significance of potential environmental impacts of a product or a system identified in the inventory analysis. According to ISO 14044 (ISO 2006b), three mandatory elements are associated with the LCIA step, such as:

(i) selection of impact categories, category indicators and characterization models,
(ii) assignment of LCI results to the selected impact categories (classification), and
(iii) calculation of category indicator results (characterization).

Optional elements of LCIA include normalization, grouping, weighting and data quality analysis (e.g. gravity analysis, uncertainty and sensitivity analysis) that are often used in impact assessment.

- ***Life cycle interpretation*** – This is the last step of LCA which evaluates the results of the inventory analysis and impact assessment. It includes the identification of the significant issues based on the results of the LCI and LCIA steps of LCA, an evaluation that considers completeness, sensitivity and consistency, and conclusions, limitations, and recommendations resulting from the assessment (ISO 2006b).

2.5.1.2 Impacts calculation in E-LCA methods

The LCIA phase intends to estimate the magnitude and significance of all the environmental impacts obtained in the LCI phase. This step combines several basic elements including characterization, normalization, damage assessment and single score of the LCI results into an indicator result.

- ***Characterization*** – The LCI results are converted to LCIA results through characterization modelling using a list of predefined factors. Using characterization factors, LCI results are converted to indicators of impact categories. Thus, this step is considered as the most important calculation in LCA. Some of the indicators are important for global perspectives, while some are regionally significant. GHGs are those gases (e.g. carbon dioxide (CO_2), methane (CH_4) and nitric oxides (N_2O), and other gases) that contribute to global warming as global warming potential on a global scale (dominated by CO_2, and hence is referred to as CO_2 eq). The characterization factor for CO_2 is 1, while it is 25 for CH_4, 56 for CO and 298 for N_2O (IPCC 2007).

- ***Normalization*** – In this step, an indicator result is converted to a normalized value according to a normalization factor. The factor can be defined according to a country, a region, or the world (Dong 2014). For example, the carbon emission is 9,950 person*year per kg CO_2 eq (European average). The normalization factor of climate change is defined as 1.01E-4 (1/9950) (according to the IMPACT 2002+ method).

- ***Damage assessment*** – In damage assessment, a number of impact category indicators are combined into an 'end-point' damage category.

  Disability-Adjusted Life Years (DALY) is characterized by the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness). For example, 13 DALY values (years/incidence) are adopted for most carcinogenic substances according to the IMPACT 2002+ method (Humbert et al. 2012).

  Potentially Disappeared Fraction of species over a certain amount of m^2 of earth surface during a certain amount of years (*PDF·m2·y*) is the unit to "measure" the impacts on ecosystems. The PDF·m2·y represents the fraction of species that have disappeared on 1 m^2 of earth surface during one year. For example, a product having an ecosystem quality score of 0.2 PDF·m2·y implies the loss of 20% of species on 1 m^2 of earth surface during one year (Humbert et al. 2012).

  MJ measures the amount of energy extracted or needed to extract the resource in the damage category of 'Resources' (Humbert et al. 2012).

- ***Single score*** – The last step of the impact assessment consists of converting the end-point categories into a single eco-point based on the standardization factors. The eco-point is known as 'single score' which is a dimensionless figure, measured in units of milli-points (mPt), which indicates the potential number of people affected by the environmental impacts in a period of one year.

2.5.1.3 E-LCA methods

Different environmental impact assessment methods have been developed, including IMPACT 2002+ (Jolliet et al. 2003), CML 2001 (Guinee 2002), Eco-indicator 99 (Goedkoop et al. 1999), EDIP 2003 (Potting and Hauschild 2004), LIME (Itsubo et al. 2004), ReCiPe 2008 (Goedkoop et al. 2009), TRACI (Bare et al. 2003), etc.

- ***IMPACT 2002+*** – IMPACT 2002+ is one of the feasible and widely used environmental impact assessment methodologies, which combines the midpoint/damage approach with all types of life cycle inventory results via several midpoint categories to several damage categories (Humbert et al. 2012). It contains 15 mid-point indicators for assessing environmental impacts including human toxicity (carcinogenic effects), human toxicity (non-carcinogenic effects), respiratory effects caused by inorganics), ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification and nutrification, land occupation, aquatic acidification, aquatic eutrophication, global warming potential, non-renewable energy, and mineral extraction. In addition, IMPACT 2002+ has four end-points (including human health, ecosystem quality, climate change, and resources) for assessing the damage. Furthermore, the IMPACT 2002+ method allows the calculation of the total environmental impacts as a single score which is very effective in comparing the impacts of different products or processes (Jolliet et al. 2003). More information can be found at http://www.quantis-intl.com/pdf/IMPACT2002_UserGuide_for_vQ2.21.pdf.

- ***CML*** – The CML method is known as a midpoint method that focuses on the impact categories defined at the midpoint level and was developed by the Centre of Environmental Science in Leiden University in 2001. The method is divided into baseline and non-baseline. The baseline method in line with ISO 14040 is the most common impact categories used in LCA (Guinee 2002). This method has been applied in various sectors, such as waste management (Suh and Rousseaux 2002) and construction materials (Kotaji et al. 2003). More information is available in the following link. http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html.

- ***Eco-indicator 99*** – Developed by PRe Consultants, Eco-indicator 99 was the first endpoint assessment method developed (Goedkoop et al. 1999). It is one of the widely-used impact assessment methods in E-LCA. This method allows the expression of the environmental impact in one single score and plays an important role in the development of other LCIA methods, such as IMPACT 2002+ and ‘ReCiPe. More information can be found at www.pre.nl/eco-indicator99.

- ***EDIP 2003*** – The Environmental Development of Industrial Products (EDIP) was developed by the Institute for Product Development (IPU) at the Technical University of Denmark (Potting and Hauschild 2004). It is a midpoint method but has a good basis for damage estimation with uncertainties. The method is valid for European and global perspectives. A total of 19 impact categories are included in the EDIP 2003 method. This method allows LCA of industrial products to support environmental analysis with preference for spatial analysis. More information is available at http://www.lca-center.dk/cms/site.aspx?p=1595.

- ***LIME*** – A Japanese life cycle impact assessment method based on endpoint modelling (LIME) was developed by the Research Center for Life Cycle Assessment at The National Institute of Advanced Industrial Science and Technology (Itsubo et al. 2004; Hayashi et al. 2006). LIME was developed with inputs from experts from around the world with special emphasis on midpoint, endpoint and weighting reflecting the environmental conditions of Japan. More information can be found at www.jemai.or.jp/english/lca/project.cfm.

- ***ReCiPe*** – This method is a follow up of Eco-indicator 99 and CML 2002. Similar to IMPACT 2002+, this method integrates midpoint and endpoint approaches in a consistent framework (Goedkoop et al. 2009). It contains 18 mid-point impact categories and three damage categories. The method is valid mostly for Europe, but also global for climate change, ozone layer depletion and resources. This method has been applied in LCA of various sectors, such as construction (Dong 2014) and building materials (Ibbotson and Kara 2013), etc. More information can be found at https://sites.google.com/site/lciarecipe/.

- ***TRACI*** – The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) developed by US EPA is a midpoint-based LCIA method for North America (Bare et al. 2003). This method provides characterization factors for LCIA, process design, industrial ecology, and sustainability metrics. Impact categories included in TRACI are ozone depletion, climate change, acidification, eutrophication, smog formation, human health impacts, ecotoxicity, and resource uses. More information can be found at www.epa.gov/ORD/NRMRL/std/sab/traci/.

2.5.1.4 Selection of LCIA method

There are essentially two approaches employed for life cycle assessment, which are the problem-oriented mid-points approach and damage-oriented end-points approach. The problem-oriented mid-points approach translates the environmental impacts into real phenomena, such as global warming, acidification, ozone depletion, eutrophication, and human toxicity, which can be evaluated using the CML, EDIP, ReCiPe and IMPACT 2002+

LCIA methods. The damage-oriented end points approach translates the mid-point impacts by modelling the damage to human beings, the environment, climate change, and resources (e.g. Ecoindicator 99, ReCiPe and IMPACT 2002+ methods) (Ortiz et al. 2009). The latter LCIA methods are comprehensive, and the impacts can be assessed to the end-point categories or even single score which is very effective for comparative analysis. However, mid-point and end-point results can be influenced due to different weighting factors of different LCIA methods. Therefore, it is important to understand the underlying concepts of weighting methods for the variability of weighting factors (Yokoi et al., 2015). For example, Dong et al. (2016) critically analyzed different LCIA methods, and found that different LCIA methods generated quite consistent results for most of the impact categories (e.g., climate change, acidification, ozone depletion, and energy resources), but higher variations were also found for some categories (e.g., ecotoxicity and human toxicity).

Since the IMPACT 2002+ method combines the advantages (e.g., impact categories and associated factors) of another three LCIA methods (i.e. Eco-indicator 99, IPCC and CML), this study selected the IMPACT 2002+ method for a comprehensive assessment (Jolliet et al. 2003; Humbert et al. 2012). Although there is no specific guideline for the selection of LCIA method, this study selected more comprehensive, well-structured, both mid-point and end-point approaches, feasible and widely used LCIA method for various applications (e.g., IMPACT 2002+) for impact assessment (Bovea and Powell, 2016; Rosado et al., 2017).

2.5.1.5 LCA assessment tools

A number of tools, especially software packages, are available to facilitate environmental impact assessment. Some of these are fully compliant with ISO standards for LCA including SimaPro, GaBi, Umberto, eBalance, EcoCalculator, etc. (Speck et al. 2015). Some of the widely used LCA software is briefly discussed in Table 2-1.

Table 2-1 - Brief introduction of LCA tools

Name	Origin	Main features	Application
SimaPro	PRé Sustainability, The Netherlands (https://simapro.com/)	• Most widely used LCA software • Handle complex LCA with uncertainities • Transparent and wide range of database • Commercial • Different versions (Direct, analyst, Developer, Single user, Multi-user, etc) • Sophisticated impact assessment and analysis option • Sensitivity analysis tool (depends on version), scenario analysis, parameter analysis	• Use in more than 80 countries • Variety of applications, such as sustainability reporting, footprinting, product design, environmental declaration, etc. • Different industries, sectors and academia
GaBi	thinkstep Global, Germany (www.gabi-software.com/)	• Easy to handle complex LCA • Sensitivity analysis tool (Monte-Carlo • analysis), scenario analysis, parameter • analysis • Different versions (GaBi Envision, GaBi Server, GaBi DfX, GaBi education) • Commercial • Complicated LCA methods and database	• More than 10,000 users • Variety of applications • Different industries and sectors, especially for automobile and electronics industry
BEES	The National Institute of Standards and Technology, USA (http://www.nist.gov/el/economics/BEESSoftware.cfm)	• Online and free • BEES database • Environmental and economic analysis based on LCA • More than 230 building products • Support multi-attribute decision analysis	• Only in construction industry
EcoCalculator	Athena Sustainable Materials Institute, Canada (http://www.athenasmi.org/our-software-data/overview/	• Spreadsheet tool with pre-defined assembly and envelope configurations • Comply with LCA methodology standards • Comprehensive and reliable • Technical knowledge is required • Own database • Commercial	• Only in construction industry

	)		
TEAM	Ecobilan-PricewaterhouseCoopers, France (http://ecobilan.pwc.fr/en/boite-a-outils/team.html)	• Allow multiple layer structure • Graphical interface • Commercial • Easy to install and use • Allow multiple databases • Comprehensive database of over 600 modules with worldwide coverage • Environmental and cost profile	• Strategic LCA application, eco-design, etc. • Limited application exists
Umberto	ifu Hamburg GmbH, Germany (https://www.ifu.com/en/umberto/?)	• Visualize material and energy flow systems • Comprehensive database with predefined transition modules • Consider environmental and economic aspects • Transparent in complex production systems • Commercial	• Variety of applications • Different industries, sectors and academia
openLCA	GreenDelta GmbH, Germany	• Modular software for LCA and sustainability assessments • Web-based open source software • Transparent and can be modified • Required technical skill • Limited databases	• Multiple applications
Quantis	Quantis, Switzerland	• Web-based software • User friendly interface • Product and company wide LCA modeling • Own water footprint and world food LCI databases • Commercial	• Multiple applications, especially for water footprint and food LCA
eBalance	IKE Environmental Technology, China	• Full-featured LCA software, especially for China • Equipped with Chinese and global databases • Commercial.	• Multiple applications, especially products manufactured in China • More than 1000 users, although new LCA software.

2.5.1.6 Life cycle inventory (LCI) databases

The use of standard LCI databases is a common practice in LCA study (Pinsonnault et al. 2014). Due to the high temporal variability of LCI databases, significant variations of LCA results are observed, and thus regional LCI databases are preferred in the LCA community (Elduque et al. 2015; Rodríguez et al. 2014). Therefore, some databases are developed from global/regional perspectives (e.g. ecoinvent), while some are based on local perspectives (e.g. CLCD). Some of the recognized and mostly used LCI databases are briefly explained below:

- ***Ecoinvent*** – Ecoinvent database developed by the Ecoinvent Centre, the Swiss Centre for Life Cycle Inventories, has the largest datasets in the world (Ecoinvent 2016). This is a widely recognized, transparent and consistent LCI database with more than 20 years of experience in LCI data compilation for different industrial sectors. The database allows access to the data on both unit process and system process levels, and it frequently updates as soon as new data is available. More than 10,300 LCI datasets are available currently in the fields of energy, agriculture, transport, bio-fuels and bio-materials, bulk and specialty chemicals, construction materials, packaging materials, basic and precious metals, metals processing, electronics, dairy, wood, waste treatment, etc. This database is extensively used for life cycle assessment, life cycle management, carbon footprint, water footprint, environmental performance monitoring, product design, eco-design and environmental product declaration. This database is integrated into the major LCA software package, including SimaPro 8 LCA software.

- ***U.S. LCI database*** – The U.S. Life Cycle Inventory (USLCI) database has been developed by National Renewable Energy Laboratory (NREL) and its partners to account for energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in the U.S. The database maintains data quality and transparency, and covers commonly used materials, products, and processes in the United States. It supports the expanded use of LCA as an environmental decision-making tool, maintains compatibility with international LCI databases and supports U.S. industry competitiveness (USLCI 2016).

- ***CPM LCA database*** – The Centre for Environmental Assessment of Product and Material Systems (CPM LCA) database has been developed by the Chalmers University of Technology, Sweden. It allows free online access to over 700 individual datasets regarding energy carriers and technologies, materials, transport, systems, agriculture, food, renewable materials, end-of-life treatment, wastes, etc.

- ***CML IA database*** – The CML-IA database has been developed by the Department of Industrial Ecology, University of Leiden. The database contains the characterization factors for all baseline characterization methods mentioned in the Handbook on LCA, such as GWP100. It offers free-access datasets that can be used in different LCA tools.

- ***Athena LCI database*** – The Athena Institute has developed the Athena LCI database mostly for building materials and products, and their associated energy use, transportation, construction and demolition. This dataset is included in Athena software tools.

- ***AusLCI database*** – The Australian National Life Cycle Inventory Database (AusLCI) was developed by the Australian Life Cycle Assessment Society with the aim to provide and maintain a national, publicly-accessible database on a wide range of Australian products and services over their entire life cycle. The database provides a consistent source of information regarding buildings and infrastructure, agriculture, bio-based materials, chemicals, electricity, transport, materials and wastes.

- ***CLCD*** – The Chinese Life Cycle database (CLCD) is a national background LCI database developed jointly by Sichuan University and IKE Environmental Technology CO. The database consists of 600 LCI datasets for key materials and chemicals, energy carriers, transport, and waste management, which represents the combination of various technologies in the Chinese market. The database is integrated into eBalance LCA software.

2.5.2 Social life cycle assessment

According to the United Nations Environment Programme (UNEP), social life cycle assessment (S-LCA) is defined as "*a social impact (and potential impacts) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal*" (UNEP 2009).

S-LCA can be used as a stand-alone method or as a complement to E-LCA, as few initiatives have been taken to include the social dimension of sustainability within the traditional framework for LCA (e.g. Valdivia et al. 2012; Blok et al. 2013). A number of studies have been found in the last decade identifying a set of valid and accepted indicators, as well as framework for social impact assessment (Weidema 2006; Dreyer et al. 2006; Jørgensen et al. 2010; Benoit et al. 2011; Traverso et al. 2013; Benoît-Norris et al. 2013; Neugebauer et al. 2015). However, a methodological framework provided for systematically conducting social assessment of products along their life cycle is still at an early stage of development (Haaster et al. 2016).

Although several individual studies exist as case studies, such as the electronic, construction process, food, tourism, automotive and energy sectors (e.g. Petti et al. 2016; Zanchi et al. 2016; Dong 2014; Martínez-Blanco et al. 2014; Manik et al. 2013; Arcese et al. 2013; Schau et al. 2012; Aparcana and Salhofer 2013), methodology for social impact assessment of construction materials is yet to be developed. In addition, only one social LCI database is currently available based on a few indicators, such as working hours, which uses a global input–output model derived from the Global Trade Analysis Project (GTAP) database and ranks country-specific sectors within supply chains by labour intensity. However, the adequacy of S-LCA methodology depends heavily on how the quantifiable and unquantifiable factors (as many as possible) are coped with. Therefore, a more intensive, case-specific or material-specific, S-LCA method is particularly important for assessing social impacts.

The overall research design in relation to the research objectives is shwon in Figure 2-5.

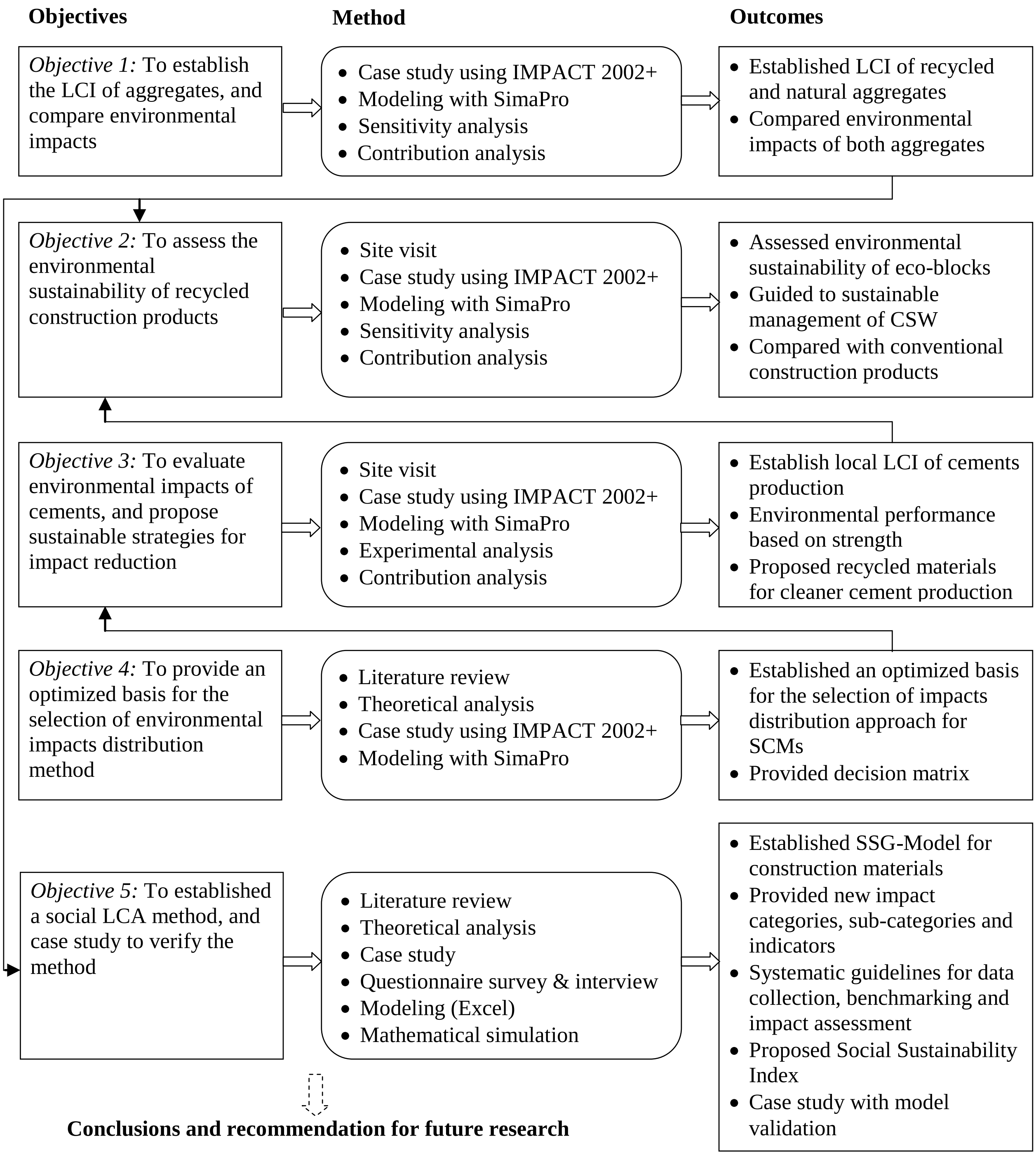


Figure 2-5 - Outline of the overall research methodology

2.6 Summary

The previous LCA studies, particularly on C&D waste, CSW, wood waste, waste glass, and construction materials and products (e.g. aggregates, cement, concrete and concrete products), have been reviewed intensively. The analysis of the reviewed literature lays a sound basis for this study. LCA has been widely used in the construction industry. However, case-specific local studies on construction materials and products are essential for maintaining the accuracy of the assessment and sustainability in the local construction sector. For LCA methodology, many aspects, in particular the use of SCMs in concrete/cement and the selection of their associated environmental impact distribution approach are unresolved issues. In addition, S-LCA methodology is still undergoing development and many issues are not clear. It is apparent from the reviewed literature that the consideration of social aspects and sustainability is neglected due to the lack of an effective and comprehensive S-LCA methodology. Therefore, the S-LCA methodology can be used to supplement LCA for assessing construction sustainability, and the guidelines of the LCA methodology for SCMs can provide a basis for the selection of appropriate approaches for assessing construction materials/products.

Using the most accepted LCA tool (e.g. SimaPro software), methodology (e.g. IMPACT 2002+) and databases, this thesis promotes the eco-innovations in the construction industry by enhancing sustainability knowledge from a life cycle perspective. In addition, the outcomes of the thesis can fill the existing research gaps in order to make sustainable decisions with regard to choosing construction materials, comparative sustainability of construction products, as well as the methodology selection for assessing the environmental performance of construction materials, and the methodology development for social sustainability performance of construction materials.

CHAPTER 3

COMPARATIVE ENVIRONMENTAL EVALUATION OF RECYCLED AND NATURAL AGGREGATES

3.1 Introduction

The construction industry is considered as an important contributor of environmental degradation and natural resource depletion. About 3 billion tonnes (t) of raw materials annually are used for the manufacturing of construction materials worldwide (Saghafi and Teshnizi 2011). Minerals are essential construction materials, but their extraction, processing, handling and uses account for about 7% of total global energy consumption. In addition, transportation of primary minerals alone is responsible for 40% of the total energy consumption by the industry (Mankelow et al. 2010). However, the construction industry is now playing an important role leading to sustainable development through the application of various sustainable tools by assessing the impacts of the whole life cycle of usage, minimizing waste generation, ensuring energy efficiency and reusing recycled materials in construction (Koroneos and Dompros 2007).

Owing to the increase in urban populations and boosting of construction activities throughout the world, a considerable amount of C&D wastes are generated along with other municipal solid wastes, such as post consumer waste glass. For example, in Hong Kong, the amount of C&D waste generation was about 6 times of that of municipal solid waste (MSW), and waste glass constituted about 3.7% of the total MSW in 2013. Therefore, the effective management of these wastes is a serious environmental concern. In addition, the construction industry needs alternative and sustainable sources of construction materials. Hence, the need to study the effective management of these wastes, and their potential recyclability, is burgeoning globally.

Landfilling of C&D waste and waste glass is not a sustainable management option due to landfill shortages and its environmental consequences. Hence, several methods have been developed to recycle and reuse these wastes as construction materials (Cyr et al. 2012). Therefore, 'reduce, reuse and recycle' approaches have become a priority option in modern waste management strategies (del Valle-Zermeno et al. 2013). For example, the recycling rate of C&D waste was ranged from 10-90% in the EU in 2010, and the EU has set an average recycling rate target of 70% by 2020. Some of the EU countries such as Belgium, the Netherlands, Switzerland and Austria have already reached the target (RILEM 2013).

Recycling of C&D waste and waste glass to produce recycled aggregates can be considered as a valuable option, not only for minimizing landfilling impacts but also for saving primary resources. Many studies have demonstrated that recycled concrete aggregates can be used as construction materials. Examples are recycled aggregates in precast concrete products (Soutsos et al. 2011), in concrete (Silva et al. 2014; Jullien et al. 2012; Rodríguez-Robles et al. 2014; Gonzalez-Fonteboa and Martinez-Abella 2008), and in concrete kerbs and floor blocks (Gayarre et al. 2013). The use of recycled aggregates in new concrete still has some technical limitations related to inferior mechanical performance and some studies found a slight increase in cement content is necessary to render the new concrete comparable to that of conventional concrete (Gonzalez-Fonteboa and Martinez-Abella 2008). However, other than concrete, the recycled aggregates can be utilized as an engineering fill, in road construction as sub-base materials (Poon and Chan 2006a; Ebrahim and Behiry 2013), and in lower grade concrete products, such as paving blocks (Poon and Chan 2007; Lam et al. 2007). In addition, recycled waste glass is also considered as a potential source of aggregate. A number of experimental studies had been conducted to assess the potential uses of waste glass as aggregates in various forms of construction. Examples are fine aggregates in cement mortar (Ling et al. 2013), in concrete (Kim et al. 2009), in concrete products (Ling and Poon 2012) and in pre-cast concrete paving blocks (Lam et al. 2007). However, no previous study has attempted to assess the environmental impacts for producing recycled aggregates from waste glass using life cycle assessment (LCA) techniques. The LCA approaches quantitatively assess environmental performance and associated impacts on products, processes or systems which can help to identify the scope of mitigation options. According to ISO 14040 (2006), "LCA methodology is more and more used as a tool for quantifying natural resources consumption and pollutant emissions with reference to the whole life cycle of mineral raw materials". In addition, Blengini et al. (2012a) identified the threefold purposes of conducting an LCA including (i) quantifying the environmental impacts and energy efficiency, (ii) improving the scope of eco-efficiency, and (iii) increasing sustainability claims as well as increasing the credibility of the products. The LCA approach is increasingly used for assessing the sustainability of construction materials and products such as cement, concrete and steel, concrete road pavement (Zhang et al. 2014; Anastasiou et al. 2015; Santero et al. 2011). Each waste management strategy (e.g. recycle and reuse, landfill, incineration, etc.) has its associated environmental impacts which should be considered by an LCA (Rigamonti et al. 2009).

It has already been mentioned that Hong Kong generates huge amounts of C&D waste and waste glass every year. Due to non-combustible and non-putrescible nature of these wastes and the running out of waste disposal sites, the management of these wastes is a serious environmental concern in Hong Kong. Mineral wastes from C&D activities and waste glass are considered to have good potential to be re-used as construction materials, especially as aggregates. In addition, Hong Kong urgently needs alternative and sustainable sources of aggregates, as the local quarry sites for aggregate production are expected to be exhausted in the near future, and the import of aggregates is not sustainable.

3.2 Present status of C&D waste and waste glass management in Hong Kong

At present, C&D waste management is a serious concern in Hong Kong due to the running out of landfill disposal sites. In Hong Kong, C&D wastes are categorized into 'mineral wastes' and 'other or mixed wastes'. The mineral C&D wastes consist mainly of sand, bricks and concrete, and they are normally deposited at public filling areas for use as a land reclamation material. The other or mixed materials, such as bamboo, plastics, wood waste, paper, vegetation and other materials are disposed of at landfills (Poon et al. 2004). According to the waste statistics published by the Hong Kong Environment Protection Department (HKEPD 2015), about 62,392 t/day of C&D waste was generated in 2013, of which 95% was delivered to public fills for land reclamation purposes, and 5% was disposed of at landfills, and the latter made up 25% of the total landfilled waste in Hong Kong. In addition, there is a privately run C&D waste recycling facility which handles only the hard mineral materials to produce recycled aggregates and granular materials for reuse in construction activities (CWM 2014). However, the current recycling rate of the C&D waste for aggregate production is very low compared to the waste disposal at public fills.

In addition, about 353 t/day of waste glass was disposed of at landfills in Hong Kong in 2013, which accounted for 3.7% of the total municipal solid waste landfilled. The recycling rate of waste glass in Hong Kong was about 17% (HKEPD 2015), which was very low when compared to other countries, such as Germany (90%), UK (44%), Japan (95%), South Korea (70%) and Taiwan (84%). Waste glass has good potential for recycling for glass manufacturing (e.g. making glass drinking bottles) and downcycling for fine aggregates production. However, due to the lack of a glass manufacturing industry in Hong Kong (and exporting waste glass is not economically feasible), waste glass was normally disposed of in landfills. To achieve high recycling rates of waste glass, source separation is very important, although high transport cost is required for collection.

This study aims to assess and compare the environmental impacts associated with aggregates production from recycled C&D waste, waste glass, and virgin materials by consequential LCA approach, which can potentially be utilized in road construction as sub-base materials and in lower grade concrete products. The study results will help the construction industry in choosing sustainable materials to minimize environmental damages. The study will also promote sustainable management of waste and efficient natural resource utilization.

3.3 Methodology

According to the ISO 14040 (2006) and ISO 14044 (2006), life cycle assessment (LCA) methodology is used to capture the environmental impacts and also the environmental benefits of a product, process or system by considering the whole life cycle. LCA consists of four main steps: (1) defining goal and scope, (2) creating life cycle inventory, (3) assessing the impacts, and (4) interpreting and analyzing the results (Marinkovic et al. 2010).

3.3.1 Goal and scope definition

This phase defines the overall objectives, system boundaries, sources of data and the functional unit of the study (Blengini 2009). Therefore, the aim of the study is to assess and compare the environmental impacts of aggregate production from virgin materials such as river sand and crushed stone (which is normally used in Hong Kong) and from recycled materials such as C&D waste and waste glass. The system boundary for assessing natural aggregates production includes the extraction, processing, transport to Hong Kong and then to use sites, and the system boundary for recycled aggregates production includes the sorting (for C&D waste), collection (for waste glass), transport to aggregate production plants, processing and then delivery to use sites. The functional unit of assessment in this study is the production of 1 t of natural fine aggregates from river sand and crushed stone vs. 1 t of recycled fine aggregates from C&D waste and waste glass, and the production of 1 t of natural coarse aggregates from crushed stone vs. 1 t of recycled coarse aggregates from C&D waste in Hong Kong.

3.3.2 Life cycle inventory (LCI) analysis

According the ISO 14040-44 series, the aim of the inventory analysis is to quantify the environmentally significant inputs and outputs of the systems by means of mass and energy balances (La Rosa et al. 2013). The LCI consists of a detailed compilation of all the environmental inputs such as material and energy, and outputs such as air emissions, water effluents and solid waste disposal at every stage of the life cycle (Blengini 2009).

In Hong Kong, more than 75% of all the primary aggregates are imported from Dongguan and Panyu in Guangdong province in mainland China. Therefore, the necessary data related to materials, energy and fuels for producing natural aggregates and also their transport to Hong Kong were collected from the respective manufacturers. In addition, the required data for producing recycled aggregates were collected from the recycled aggregate producers in Hong

Kong as the first hand data. The functional unit data was calculated based on the company's total production of aggregates and total energy consumption in 2013. Therefore, most of the process data was not separated, while the process data for sorting of C&D waste was collected separately (Table 3-1 and Table 3-2).

The China Light and Power (CLP) and the Chinese Life Cycle Database (CLCD) were used as the upstream data sources (e.g. electricity generation, fuel consumption and transportation) for this LCA. The CLCD is a national LCI database for key materials and chemicals, energy and energy carriers, transport, and waste management in the Chinese market. Because the majority of the materials in Hong Kong come from (and are produced in) China, the use of CLCD database would be more appropriate rather than other databases. However, some of the materials and processes are not available in the CLCD database. Hence, the ELCD database (European reference Life Cycle Database) was used to fill this gap (Table 3-2). Finally, all the steps related to the collection and transportation of wastes and aggregates production are modeled and assessed by using SimaPro 8.0.1 software. SimaPro is one of the most widely used and accepted LCA tools. It helps to model various products and processes comprehensively and analyzes the results interactively for achieving sustainability goals (PRé Consultants 2013).

3.3.3 Life cycle impact assessment (LCIA) and impact analysis

The LCIA phase intends to estimate the magnitude and significance of all the environmental impacts obtained in the LCI phase. This step consists of three basic elements including (i) selection of impact categories, (ii) classification and characterization, and (iii) aggregation the LCI results into an indicator result (Marinkovic et al. 2010).

There are essentially two approaches employed for life cycle assessment, which are problem-oriented mid-points approach and damage-oriented end-points approach. The problem-oriented mid-points approach translates the environmental impacts into the real phenomena, such as global warming, acidification, ozone depletion, eutrophication, and human toxicity which can be evaluated using the CML, EDIP, ReCiPe and IMPACT 2002+ LCIA methods. The damage-oriented end points approach translates the mid-point impacts by modeling the damage to human beings, environment, climate change, and resources (e.g. Ecoindicator 99, ReCiPe and IMPACT 2002+ methods) (Ortiz et al. 2009). Since the IMPACT 2002+ method combines the advantages of another three LCIA methods (i.e. Eco-indicator 99, IPCC and CML), this study selected the Impact 2002+ method for comprehensive assessment. The IMPACT 2002+ method contains 15 mid-point indicators for assessing the environmental impacts including human toxicity (carcinogenic effects) (CG), human toxicity (non-carcinogenic effects) (N-CG), respiratory effects caused by inorganics (RIn), ionizing radiation (IR), ozone layer depletion (OL), respiratory organics (ROg), aquatic ecotoxicity (AEco), terrestrial ecotoxicity (TEco), terrestrial acidification and nutrification (TAci), land occupation (LOc), aquatic acidification (AAci), aquatic eutrophication (AEu), global warming potential (GWP), non-renewable energy (N-Re), and mineral extraction (MEx). In addition, IMPACT 2002+ has 4 end-points (including human health, ecosystem quality, climate change, and resources) for assessing the damages. Furthermore, the IMPACT 2002+ method allows the calculation of the total environmental impacts (based on the assessed mid-point and end-point indicators) to a single score which is very effective in comparing the impacts of different products or processes. The principle of environmental impacts calculation by the IMPACT 2002+ method is given in Appendix A (Table A1) (Jolliet et al. 2003). Some of the indicators are important for global perspectives and some are regionally significant.

The avoided impacts of disposing an equivalent waste glass at landfills are considered in this study, as landfilling is the marginal technology for waste glass management in Hong Kong. Although the marginal technology for C&D waste management is public filling, the authors still think the avoided impacts need to be considered in this study. This is because Hong Kong is acutely short of public filling capacities as the harbor and seafronts have mostly been filled up already. The C&D waste is currently temporary stored in ‘fill banks’ pending transport to marine sites (about 200 km away) in mainland China for disposal. Therefore, the credit for discounting these impacts (C&D waste collection and transport to temporarily storage fill bank, and then to Tai-Shan in mainland China) to the recycled aggregate production is necessary, as the hard portion of C&D waste can be recycled and utilized as valuable materials for road sub-base and lower grade concrete applications in lieu of using natural aggregates. Therefore, the net environmental impacts of recycled aggregate production are assessed by considering the induced impacts including all the impacts associated with the collection, sorting and the production of recycled aggregates, and the avoided impacts which are the sum of all the impacts associated with the collection, sorting, transporting and landfilling of wastes (for waste glass), transporting to fill sites (for C&D waste).

3.4 Description of the aggregate production process

This section provides the information and assumptions used to construct the LCA model within the system boundary. In LCA studies, some logical assumptions are coherently needed as it is almost impossible to model aggregate production strictly following the real process step by step (Blengini et al. 2012a). The transport information for the concerned materials and aggregates, and the energy requirements for aggregate production are summarized in Tables 3-1 and 3-2.

Table 3-1 - Materials and transport data of aggregate production

Materials	Locations	Transport type	Distance	Upstream database
Natural aggregates (RS, River sand)	Extraction sites to Dongguan, Guangdong Province, China *	Trucks (30 t)	20 km	CLCD 2010e
	Dongguan to Hong Kong Port	Inland barge	128 km	CLCD 2010a
	Hong Kong Port to utilization sites *	Trucks (30 t)	30 km	CLCD 2010e
Natural aggregates (CS, Crushed stone)	Extraction sites to Dongguan, Guangdong Province, China *	Trucks (30 t)	50 km	CLCD 2010e
	Dongguan to Hong Kong Port	Inland barge	128 km	CLCD 2010a
	Hong Kong Port to utilization sites *	Trucks (30 t)	30 km	CLCD 2010e
Recycled C&D waste	C&D waste generation sites to recycled aggregate production plant *	Trucks (30 t)	45 km	CLCD 2010e
Recycled aggregates (C&D waste)	Recycled aggregate production plant to utilization sites *	Trucks (30 t)	40 km	CLCD 2010e
C&D waste (to fill sites)	C&D waste generation sites to temporary storage (fill banks), and then to fill sites in mainland China*	Trucks (30 t); Inland barge	35 km; 200 km	CLCD 2010e CLCD 2010a
Recycled waste glass	Waste glass collection sites to recycled aggregate production plant *	Trucks (18 t)	50 km	CLCD 2010e
Recycled aggregates (waste glass)	Recycled aggregate production plant to utilization sites *	Trucks (30 t)	40 km	CLCD 2010e
Waste glass (landfill)	Waste glass collection sites to landfill sites *	Trucks (6 t); Trucks (30 t)	6 km; 35 km	CLCD 2010e

* The distance vary due to different geographic locations (the average distance is considered)

Table 3-2 - Energy requirements of the production of aggregates

Materials	Activity	Energy requirements	Sources of data	Upstream database
Natural fine (RS)	Extracting, on-site handling	69 MJ/t (diesel)	Measured*	CLCD 2010d
Natural fine (CS)	Extracting, screening, crushing and sieving	27 MJ/t (electricity) & 50 MJ/t (diesel)	Measured*	CLP 2014; CLCD 2010c,d
Natural coarse (CS)	Extracting, screening, crushing and sieving	22 MJ/t (electricity) & 51 MJ/t (diesel)	Measured*	CLP 2014; CLCD 2010c,d
Recycled fine (C&D waste)	Sorting (on-sites)	35 MJ/t (diesel)	Measured*	CLCD 2010d
	Processing (crushing, sieving, on-site transport and handling)	11 MJ/t (electricity) & 21 MJ/t (diesel)	Measured*	CLP 2014; CLCD 2010c,d
Recycled coarse (C&D waste)	Sorting (on-sites)	35 MJ/t (diesel)	Measured*	CLCD 2010d
	Processing (crushing, sieving, on-site transport and handling)	4 MJ/t (electricity) & 21 MJ/t (diesel)	Measured*	CLP 2014; CLCD 2010c,d
Recycled fine (waste glass)	On-site transport and handling, milling and sieving	47 MJ/t (electricity) & 21 MJ/t (diesel)	Measured*	CLP 2014; CLCD 2010c,d
Waste glass landfill	Landfill of glass/C&D waste	Referring to the ELCD database	--	ELCD, 2013

* Measured, calculated based on the company's yearly production of aggregates and energy consumption

3.4.1 Natural aggregates

The system boundary and processes for aggregate production from natural materials are shown in Figures 3-1 and 3-2. The processes for producing natural aggregates comprise several individual stages. The first stage is the raw material extraction which includes extraction by mining (for crushed stone), and excavation and collection (for river sand). This stage includes the use of energy for blasting, crushing, dredging, transit and offloading. The processing stage includes the bulk handling of aggregates by mechanical shovels for loading-unloading onto trucks, and also for feeding into crushers. Before crushing, scalping screening is used to remove large objects. Depending on size requirements, different types of crusher are used, such as jaw crushers, rotary mills, and cone crushers. In addition, grinding machines with screeners are used to produce fine aggregates from crushed stones. The on-site transport stage includes aggregate transport from the extraction site to the processing site then to the vessel loading locations by 30 t trucks. The off-site transport stage includes the aggregate transport to Hong Kong by inland-coastal barges, and then to use sites in different areas of Hong Kong. The necessary data related to transport and energy inputs for producing natural aggregates are given in Table 3-1 and Table 3-2. Noted that natural fine aggregates from crushed stone are commonly used in Hong Kong.

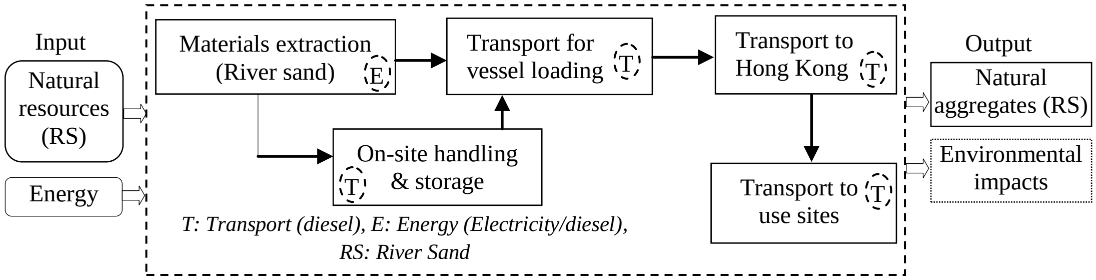


Figure 3-1 - System boundary for producing natural fine aggregates from river sand

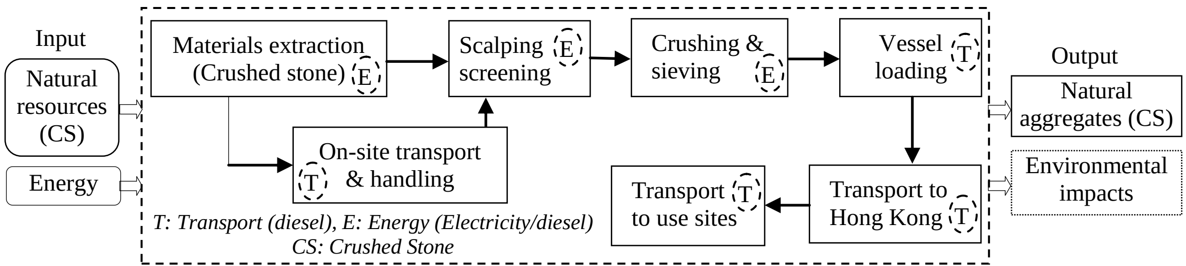


Figure 3-2 - System boundary for producing natural aggregates from crushed stone

3.4.2 Recycled aggregates from C&D waste

The typical structure of C&D waste management in Hong Kong is shown in Figure 3-3. There are three possible ways to manage C&D waste in Hong Kong. Firstly, after on-site sorting of mixed C&D waste, the mineral wastes are transported to public fill reception facilities, and the other wastes are sent to landfill sites, and recyclable materials are sent to recycling facilities. Three strategic landfills, namely, North East New Territories (NENT) Landfill, South East New Territories (SENT) Landfill, and West New Territories (WENT) Landfill are operated in Hong Kong, which will be running out by 2018 (HKEB 2011). In addition, there are two off-site sorting facilities, namely Tseung Kwan O Area 137 Sorting Facilities and Tuen Mun Area 38 Sorting Facilities. Secondly, the mix wastes are transported to off-site sorting facilities, and then sent to public fill or landfill sites after sorting according to the quality of wastes, and the recyclable materials are sent to recycling facilities. Thirdly, after recovering some of the recycled materials on-site, the rest of the mix wastes are then sent to the landfill sites directly. The system boundary and processes for producing recycled aggregates from C&D waste are given in Figure 3-4.

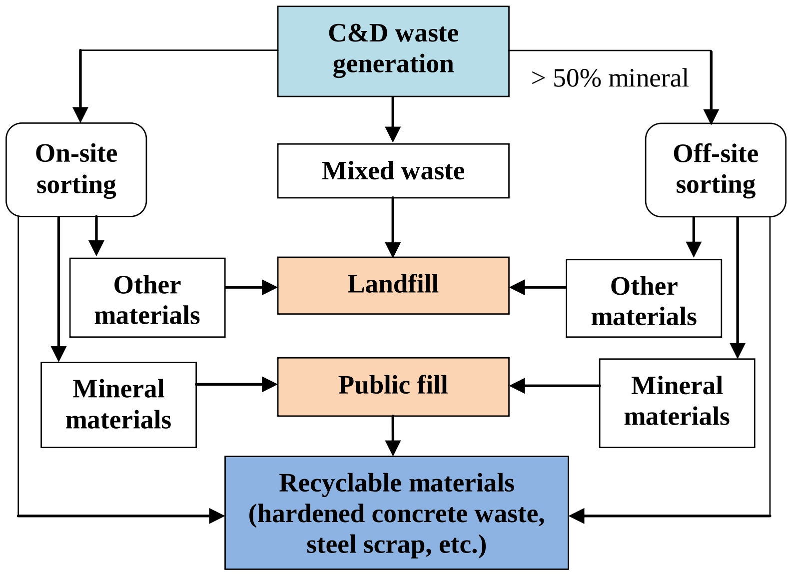


Figure 3-3 - The structure of C&D waste management in Hong Kong

This study considered all the three possible ways of transporting the recycled C&D waste to the recycled aggregate production plant at Lung Kwu Tan (Tuen Mun) in Hong Kong. The sorted good quality C&D waste is transported to the aggregates manufacturing plant. Based on the geographic locations of the recycled aggregate production plant, 10 locations were identified as the sources of C&D waste and the average transport distances to the recycling plant and temporary public fills by 30 t trucks were calculated. The average distances from the sources of C&D waste generation to the recycling plant and public fill sites were 45 and 35 km, respectively. At the recycling plant, the C&D waste goes through several stages of processing.

The collected C&D waste are sorted and then fed into hoppers for crushing. Mechanical shovels are normally used for handling the bulk materials for loading-unloading onto the trucks and feeding into the hoppers. Depending on the requirements on aggregate size, different types of crushers and sieves are used. The produced recycled aggregate is then transported to use sites. The necessary data related to transport and energy inputs for producing recycled aggregates from C&D waste are given in Table 3-1 and Table 3-2.

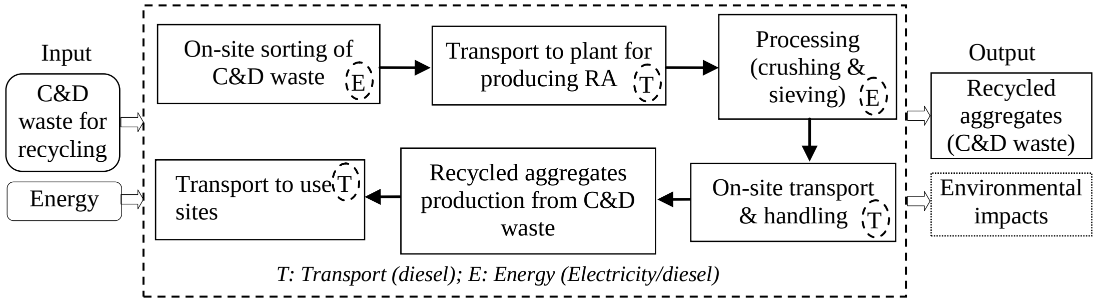


Figure 3-4 - System boundary and processes of recycled aggregates produced from C&D waste

3.4.3 Recycled aggregates from waste glass

A schematic diagram for recycled fine aggregates production from recycling post consumer beverage glass bottles is shown in Figure 3-5. There are three possible ways of waste glass collection in Hong Kong. Firstly, the post consumer glass bottles are recovered from designated recycling bins. Secondly, the bottles are collected from hotels and shops, and thirdly, from refuse transfer stations (RTS) and landfill sites. Hence, the average distance for waste glass collection and transport (by 18 t trucks) to the recycling plant is estimated (about 50 km).

After transporting to the plant, the collected waste glass bottles are then milled by a hammer mill to produce glass sand (fine aggregates) after passing through a sieve of designated size (3.55 mm). Mechanical forklifts are used for on-site transport, and also mechanical conveyers are used to transport the finished products to the storage bunker.

According to the HKEPD report, more than 80% of the waste glass was not recycled in 2013 (HKEPD 2015), and thus it was disposed of at landfills with other municipal solid wastes (MSW). Moreover, about 65% the total collected MSW in Hong Kong is transferred to landfills using refuse transfer stations (RTS). The average distance for MSW collection from the point of generation to RTS is about 6 km, using 6 t refuse collection vehicles (Saman 2013). In the RTS, the collected wastes are compacted into bigger containers which are then transported to the landfills by using 30 t trucks (the calculated average distance is about 35 km). In addition, the environmental impacts of waste glass landfilling are considered as avoided impacts. All the steps for producing recycled fine aggregate from waste glass were modeled by using the SimaPro 8.0.1

software. The transport and energy input data for producing recycled aggregates from waste glass are given in Table 3-1 and Table 3-2.

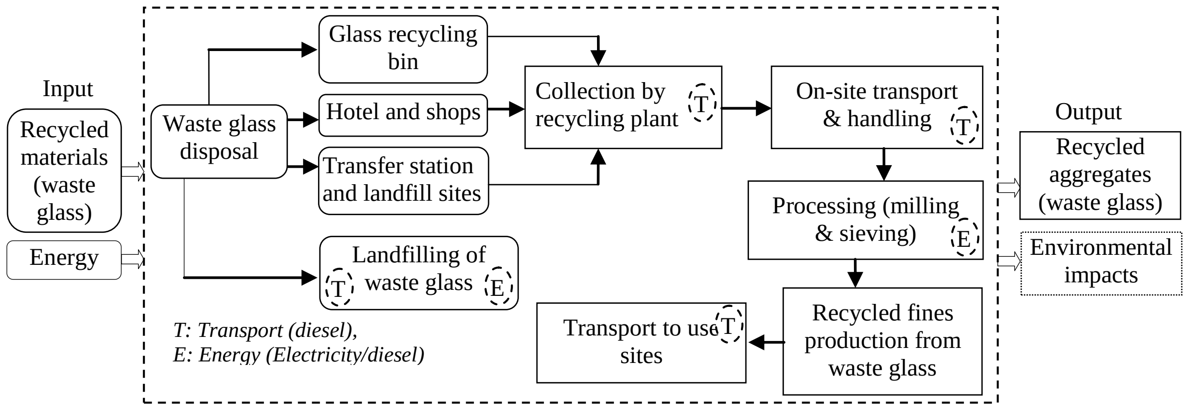


Figure 3-5 - System boundary and processes of recycled fine aggregates produced from waste glass

Based on the geographic locations in Hong Kong, eight construction sites were selected as potential use sites of natural and recycled aggregates and the average transport distances from the recycled aggregate manufacturing plant and Hong Kong Port (for natural aggregates) to the use sites by 30 t trucks were calculated (Table 3-1).

3.5 Results and discussion

In this study, the production of two types of aggregates were assessed viz, (i) fine aggregates (<5 mm) produced from natural materials (e.g. river sand and crushed stone) and recycled materials (C&D waste and waste glass); and (ii) coarse aggregates (5-20 mm) from virgin material (e.g. crushed stone) and recycled materials (e.g. C&D waste).

3.5.1 Fine aggregates production

Within the system boundaries, assumptions and methodology used in the study, the estimated mid-point environmental impacts for producing 1 t of fine aggregates is shown in Table 3-3. It is estimated that about 341 MJ of non-renewable energy is needed to produce 1 t of fine aggregates from river sand with the process emitting 23 kg CO_2 eq greenhouse gases (GHGs), whereas 518 MJ energy is needed for crushed stone with 33 kg CO_2 eq GHG emission.

When producing recycled aggregates, the LCA finding indicates that about 12 kg CO_2 eq/t GHG is emitted for producing 1 t of recycled fine aggregate from C&D waste. Similarly, approximately 9 kg CO_2 eq GHG is emitted for producing 1 t of recycled fine aggregate from locally generated waste glass. The impacts of global warming potential as GHG emissions is a good example for representing the impacts of non-renewable energy consumption, as these two indicators follow each other. Positive values indicate the induced impact, whereas negative values indicate the net impacts saving taking into account the avoided impacts.

Table 3-3 - Summary of the cumulative impacts of fine aggregate production

Impact category	Impact symbol	Unit	Natural fine (RS)	Natural fine (CS)	Recycled fine (C&D waste)	Recycled fine (WG)
Carcinogens	CG	kg C_2H_3Cl eq	0.23	0.05	0.05	-0.27
Non-carcinogens	N-CG	kg C_2H_3Cl eq	0.02	0.03	0.02	-0.49
Respiratory in-organics	RIn	kg PM 2.5 eq	0.03	0.05	0.03	0.02
Ionizing radiation	IR	Bq C-14 eq	40	82	51	-75
Ozone layer depletion	OL	kg CFC-11 eq	8.99E-07	9.91E-07	4.43E-07	-1.35E-05
Respiratory organics	ROg	kg C_2H_4 eq	0.02	0.02	0.006	-0.02
Aquatic ecotoxicity	AEco	kg TEG water	462	879	282	-3032
Terrestrial ecotoxicity	TEco	kg TEG soil	43	44	25	-1079
Terrestrial acid/nutri.	TAci	kg SO_2 eq	0.98	1.29	0.98	0.54
Land occupation	LOc	m^2org.arable	0.01	0.01	0.008	-0.13
Aquatic acidification	AAci	kg SO_2 eq	0.14	0.19	0.13	0.06
Aquatic eutrophication	AEu	kg PO_4 P-lim	0.0006	0.0007	0.0003	-0.27
Global warming potential	GWP	kg CO_2 eq	23	33	12	9
Non-renewable energy	N-Re	MJ primary	341	518	235	156
Mineral extraction	MEx	MJ surplus	0.14	0.10	0.11	-0.21

[Note: RS, River sand; CS, Crushed stone; C&D waste, Construction & demolition waste; WG, waste glass]

Based on the IMPACT 2002+ methodology, the study characterized the associated impacts for producing the natural and recycled fine aggregates and the results are shown in Figure 3-6 (See Appendix A3 for calculations). It is impractical to compare the different impacts categories, as they are not equally weighted and important. Hence, the present study compares the impact between the different aggregates. The figure shows that recycled fine aggregates from C&D waste induce lower impacts for most of the considered impact indicators as compared to that of the natural fines. Similarly, higher negative impacts (e.g. higher saving) can be achieved in producing recycled fine aggregates from waste glass compared to natural fines (Figure 3-6).

Regarding the differences between the impacts for different sub-processes, it was found that natural aggregates from crushed stone are associated with 14% higher GHG due to the longer transport distances from the extraction sites (mainly in mainland China to the final utilization sites, when compared to the transport distances of that of the C&D waste) (see Table 3-1). However, GHG emissions associated with the processing activities were not significantly different for both the natural and recycled aggregates. Regarding energy consumption, the production of recycled aggregates is still more economical as they are produced from recycled waste materials.

In addition, the values of all other indicators, such as human toxicity, mineral extraction, aquatic and terrestrial ecotoxicity, ozone layer depletion, acidification potential, aquatic eutrophication and respiratory effects of the recycled aggregates from both C&D waste and waste glass are much lower than the natural aggregates. For example, about 40% and 60% lower impacts on respiratory damage as PM2.5 eq emission are observed for the production of recycled aggregates from C&D waste and waste glass, respectively, compared to that of crushed stone. In addition, the corresponding impact on acidification potential (for both terrestrial and aquatic acidification) are about 25% and 59% lower for producing recycled fines from C&D waste and waste glass, respectively.

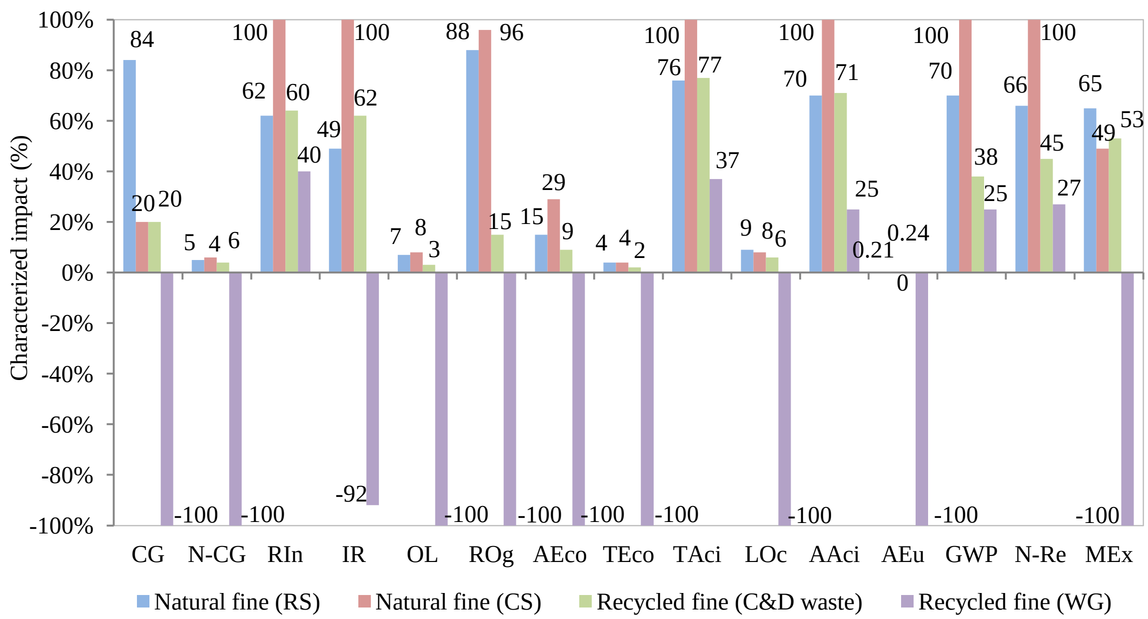


Figure 3-6 - Comparison of characterized impacts of fine aggregates production

There are four end-point indicators for damage assessment; human health, ecosystem quality, climate change and resources, which are calculated from all the mid-point indicators (see Appendix A1 and A3). The comparative damage assessment for producing fine aggregates is shown in Figure 3-7. Crushed stone shows the highest impact (100%) on human health, followed by river sand (64%), whilst lower impacts are recorded for both the recycled fine aggregates (64% for C&D waste and 33% for waste glass) compared to crushed stone. Similarly, natural fines aggregates production is associated with higher changes or damage in the ecosystem quality (17-21%), while lower for recycled fine aggregates (15% to -100%). Higher climate change impact is found for the two natural fine aggregates, e.g. crushed stone (100%) and sand river (70%), while lower impacts are observed for C&D waste (36%) and waste glass (27%). In addition, higher resource consumption or resource damage is associated with natural fines aggregates (66-100%), while much lower is found for the recycled fine aggregates (45% for C&D waste and 30% for waste glass).

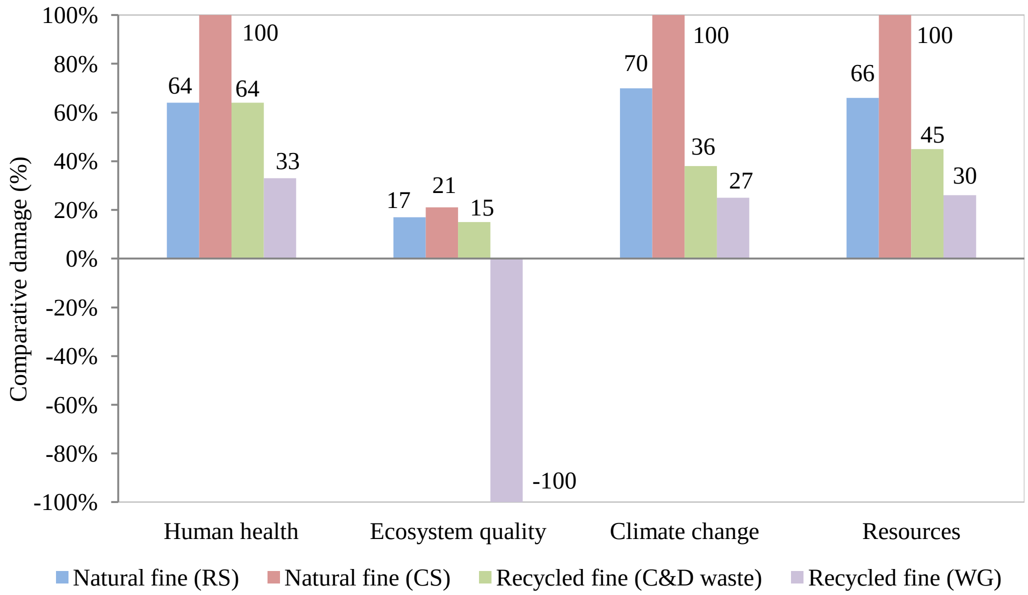


Figure 3-7 - Damage assessment of fine aggregates production

The final step of the impact assessment consists of converting the categories into a single eco-point based on the standardization factors (see Appendix A, Tables A3 and A4 for relevant factors and calculations). The eco-point is known as 'single score' which is a dimensionless figure, measured in units of milli-points (mPt), which indicates the potential number of people affected by the environmental impacts in a period of one year. The net eco-point for aggregate production is shown in Figure 3-8. The contribution of different stages to the total eco-point for aggregate production is shown in Appendix A (Table A2). The Figure shows that the production of fine aggregate from crushed stone has a single score environmental impact equivalent to 11.89 mPt (about 17% for extraction and handling, 23% for processing and 60% for transporting from extraction sites to the utilization sites), whereas 7.88 mPt is recorded from river sand (about 40% for extraction and handling and 60% for transporting the materials), 6.11 mPt for recycled fine aggregates from C&D waste (about 10.20 mPt for producing recycled aggregates, -4.09 mPt is avoided due to C&D waste collection and transport to fill sites), and 3.20 mPt for recycled fine aggregates from waste glass (about 13.56 mPt for producing recycled aggregates, -10.36 mPt is avoided due to minimizing waste glass collection, transport and landfilling) (see Appendix A, Table A2). The impacts contribution of different damage categories to the total eco-points is also shown in Figure 3-8. The Figure demonstrates that producing fine aggregates from recycled materials can significantly reduce the total environmental load when compared with those using virgin materials (about 49% for recycled fine aggregates from C&D waste instead of crushed stone, and 59% for waste glass instead of river sand). It is noted that the avoided impacts have significantly contributed to lowering the environmental impacts of recycled aggregates. For example, about 40% of the total impact can be avoided for recycled aggregates from C&D waste. However, compared to natural aggregates (crushed stone), recycled aggretages from C&D waste still has environmental benefits even except the avoided impacts (11.89 and 10.2 mPt, respectively), but significantly higher (about 40%) for recycled aggregates from waste glass compared to river sand.

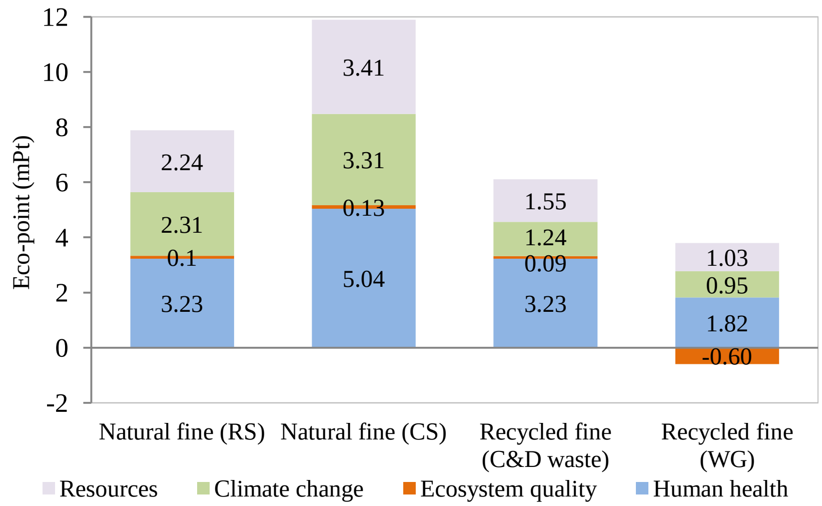


Figure 3-8 - Single score of impacts of fine aggregates production

3.5.2 Coarse aggregates production

The estimated environmental impacts for producing 1 t of coarse aggregates are shown in Table 3-4. It can be seen that about 32 kg CO_2 eq GHGs are emitted for producing 1 t natural coarse aggregates from crushed stone, whereas about 11 kg CO_2 eq GHGs are emitted to produce recycled coarse aggregates from C&D waste. Therefore, similar to the recycled fine aggregates from C&D waste, significant other environmental impacts can be reduced for producing recycled coarse aggregates instead of obtaining coarse aggregates from natural sources (Table 3-4). For example, about 40% lower PM2.5 eq emission is found for recycled coarse from C&D waste, compared to the natural coarse from crushed stone. In addition, about 26% lower acidification potential (for both terrestrial and aquatic acidification) is associated with recycled coarse from C&D waste than natural coarse from crushed stone.

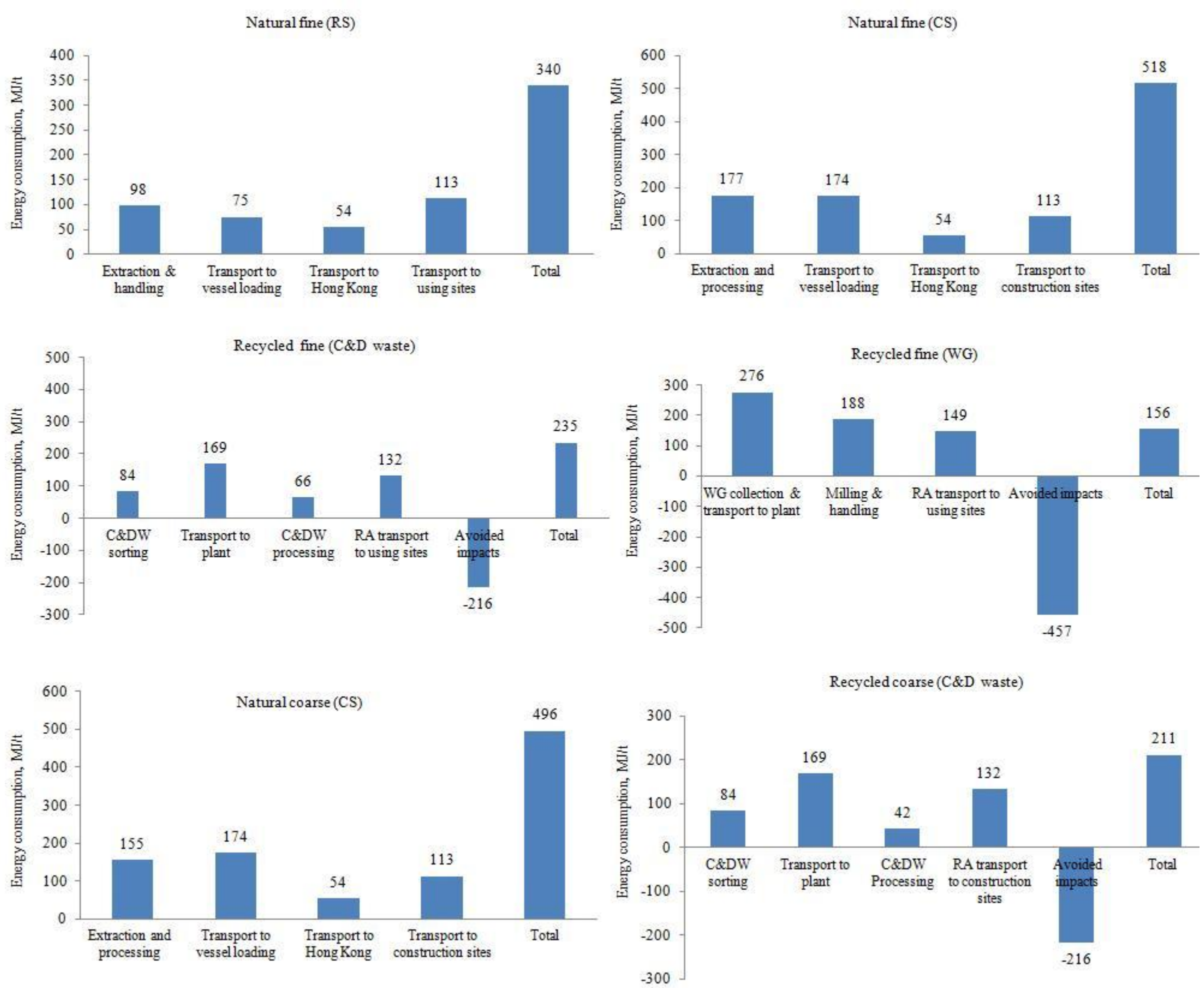
Table 3-4 - Summary of total impact of coarse aggregate production

Impact category	Impact symbol	Unit	Natural coarse (CS)	Recycled coarse (C&D waste)
Carcinogens	CG	kg C_2H_3Cl eq	0.05	0.05
Non-carcinogens	N-CG	kg C_2H_3Cl eq	0.03	0.01
Respiratory in-organics	RIn	kg PM 2.5 eq	0.05	0.03
Ionizing radiation	IR	Bq C-14 eq	72	38
Ozone layer depletion	OL	kg CFC-11 eq	9.88E-07	4.38E-07
Respiratory organics	ROg	kg C_2H_4 eq	0.02	0.005
Aquatic ecotoxicity	AEco	kg TEG water	821	204
Terrestrial ecotoxicity	TEco	kg TEG soil	44	25
Terrestrial acid/nutria.	TAci	kg SO_2 eq	1.27	0.95
Land occupation	LOc	m^2org.arable	0.01	0.008
Aquatic acidification	AAci	kg SO_2 eq	0.19	0.13
Aquatic eutrophication	AEu	kg PO_4 P-lim	0.0007	0.0003
Global warming potential	GWP	kg CO_2 eq	32	11
Non-renewable energy	N-Re	MJ primary	496	211
Mineral extraction	MEx	MJ surplus	0.10	0.11

Similar to the recycled fine aggregates, the study reveals that producing recycled coarse aggregates from C&D waste induces 38%, 30%, 66% and 57% lower impacts on human health, ecosystem quality, climate change and resources, respectively than producing natural coarse aggregates. Regarding the net eco-point, the single score of the environmental load for producing 1 t of natural coarse aggregate is 11.5 mPt, while 5.58 mPt is observed for producing 1 t of recycled coarse aggregates from C&D waste. The findings indicate that about 51% of the total environmental loads can be saved for producing recycled coarse aggregate compared to that of natural coarse aggregates.

3.5.3 Contribution analysis

The results of the life cycle assessment of the total non-renewable energy consumption for different types of aggregate production are presented in Figure 3-9. The Figure shows that the transportation (e.g. extraction sites to vessel loading sites, vessel loading sites to Hong Kong and then to use sites) of the natural fine aggregates accounts for the highest fraction of the energy input (about 71% for river sand and 66-69% for crushed stone), followed by extracting and handling (29% for river sand and 31-34% for crushed stone). Similarly, the transportation of C&D waste and waste glass to the recycled aggregate production plant and then the produced recycled aggregates to use sites is responsible for 67-70% (for C&D waste) and 69% (for waste glass) of the total energy consumption, and the rest (30-33%) is used for the on-site sorting and handling, and processing of the C&D waste, and 31% for waste glass processing and handling. Similarly, for both natural and recycled aggregates, transportation is associated with about 70% of the impacts related with all other categories.



[Note: C&D waste, construction and demolition waste; WG, waste glass; RA, recycled aggregates]

Figure 3-9 - Life cycle energy consumption of aggregate production

3.5.4 Sensitivity analysis

The LCA results may be affected by various uncertainties (Beccali et al. 2010), and hence, sensitivity analysis helps to verify the validity of the collected data and the scientific assumptions of the model. Bjorklund (2002) have identified several factors as the uncertainty of LCA results, such as parameter and model uncertainty, uncertainty due to choices, spatial and temporal variability. In addition, Clavreul et al (2012) identified several methods for uncertainty analysis of waste LCA study, namely selection of methods, sensitivity analysis (contribution analysis, perturbation analysis and combined sensitivity analysis), uncertainty propagation (choice of representation, uncertainty propagation for all scenarios and discernibility analysis), and uncertainty contribution analysis. Therefore, this study conducted a sensitivity analysis to analyze the influence of input parameters on the LCA outcomes by calculating different scenarios suggested by Bjorklund (2002).

Based on the above findings (base case analysis), a sensitivity analysis was carried out to assess the effect of varying the transport distance of the waste materials on the total environmental impacts (e.g. single score). The transport distance of the waste materials to the recycling plant is the major factor affecting the results of the recycled aggregates. The findings are presented in Table 3-5.

In this sensitivity analysis, two scenarios of transport distance variation (e.g. ±10 and ±20%) were considered and then compared with the base case. The results indicate that less than 6% of the total environmental impacts are influenced by a 10% increase or reduction of transport distance for C&D waste transport to the recycled aggregate production plant. For recycled fine aggregate produced from waste glass, a variation of ±10% transport distance for waste glass collection and transport to the aggregate manufacturing plant would induce a 20% change of the total environmental burdens (either an increase or a decrease of net saving).

Similarly, ±20% increase or reduction in the transport distance of waste collection would cause a less than 12% increase or decrease of total environmental loads for producing recycled aggregates from C&D waste. However, an equal variation would cause about 38% change than the base case for producing recycled aggregates from waste glass.

The above analysis shows that even 20% increase or reduction in the transport distance of waste collection does not affect the results significantly for the production of recycled aggregates production from C&D waste. But the results show that, recycled aggregates production from waste glass is more sensitive to the waste collection and transport distances to the manufacturing plants. However, significant environmental gains can still be achieved by producing recycled aggregates from both C&D waste and waste glass, even with 20% higher waste collection and transport distances (about 43% saving is observed from recycled fine aggregates from C&D waste compared to natural fine aggregates from crushed stone, and 44% for recycled fine aggregates from waste glass compared to river sand).

Table 3-5 - Sensitivity analysis by varying distances for waste collection

Transport distance	Recycled fine from C&D waste (mPt)	Recycled coarse from C&D waste (mPt)	Recycled fine from waste glass (mPt)
Base case	6.11	5.58	3.20
+10	6.45	5.93	3.80
-10	5.76	5.23	2.58
Variation (%)	*5.27-5.72*	*5.90-6.27*	*19.38-18.75*
Base case	6.11	5.58	3.20
+20	6.80	6.28	4.42
-20	5.41	4.88	1.97
Variation (%)	*10.14-11.45*	*11.15-12.54*	*38.44-38.13*

The critical transport distances for recycled materials have been calculated above which the recycling option would no longer be the most sustainable one. The total impacts have been then compared with the natural aggregates (shown in Figure 3-10). For recycled aggregates from C&D waste, the critical transport distance is about 170% higher compared to the base case, whereas it is about 85% higher for recycled fine from waste glass. The critical transport distance for recycled aggregates from C&D waste was 122 km, whereas it is about 93 km for recycled aggregates from waste glass. However, it is expected that recycled materials will not be exceed these critical transport distances in Hong Kong.

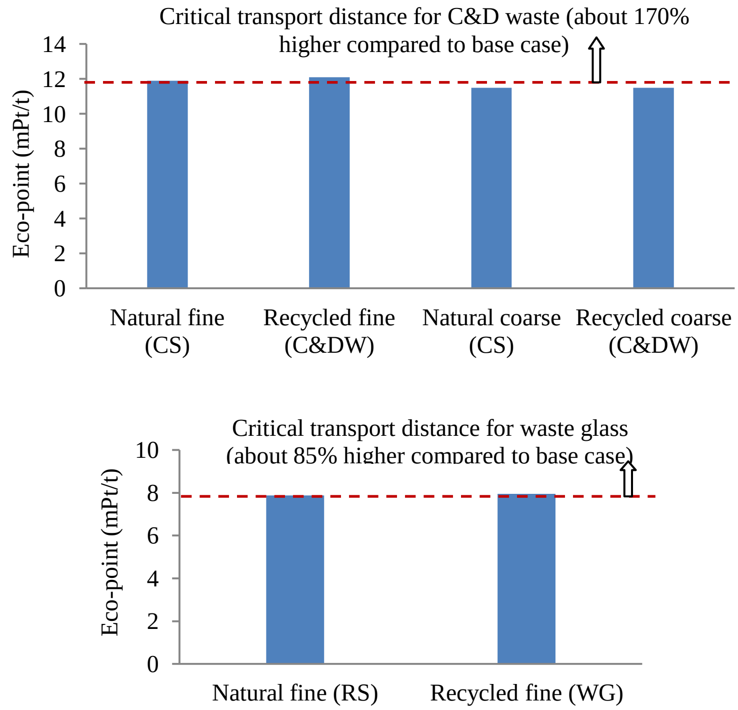


Figure 3-10 - Critical transport distance for recycled materials

3.5.5 Comparison with other studies

A comparison of the findings from this study with others is given in Table 3-6. However, it should be noted that a direct apple to apple comparison is not possible between different LCA studies due to the differences in geographical location, waste management system, data quality, energy mix, consideration of end-of-life scenarios, fuel consideration, processes, as well as system boundaries.

It is noted that about 232 MJ energy consumption and 14 kg CO_2 eq GHG emissions are associated with the production of 1 t natural aggregates from limestone (Estanqueiro, 2011), whereas 496-518 MJ energy consumption with 32-33 kg CO_2 eq GHGs are associated with the production of the same amount of natural aggregates from crushed stone in this study. The latter is about 2x that of the former. This is mainly due to the much short transport distance (43 km) in the Estanqueiro (2011) study than that of the present study (188-208 km).

For recycled aggregates production, it has been reported that about –250 to 246 MJ of energy were required (with –14 to 16 CO_2 eq GHG emissions) for producing 1 t recycled aggregates from C&D waste (Butera et al. 2015; Simion et al. 2013; Blengini and Garbarino 2010). The values found from the present study are about 211 to 235 MJ energy consumption and about 11 to 12 kg CO_2 eq GHG emissions. However, the values for producing recycled aggregates from waste glass is significantly lower (e.g. about 156 MJ energy consumption with 9 kg CO_2 eq GHG emissions).

The variation is largely due to the different transport distances and different considerations. For example, about 25-30 km of transport distances from the generation sites to the construction sites were considered by Blengini and Garbarino (2010), whereas 65 km transport distance was considered by Butera et al. (2015), and about 85-95 km transport distance for waste generation/collection sites to processing and then to use sites are considered in this study. In addition, Blengini and Garbarino (2010) also considered other avoided impacts due to landfill disposal, etc.

Table 3-6 – Comparison of results of different studies

Study	Energy consumption (MJ/t)	GHG emissions (kg CO_2 eq /t)	System boundary
Natural aggregates			
Simion et al. 2013 (Natural inert)	1664	103	Cradle-to-gate
Estanqueiro, 2011 (Limestone)	232	14	Cradle-to-site
Blengini et al. 2007 (Sand)	152	10	Cradle-to-gate
This study (Crushed stone)	496 - 518	32 - 33	Cradle-to-site
This study (River sand)	341	23	Cradle-to-site
Recycled aggregates			
Lamb et al. 2011 (Misc. aggregates)	--	6	Cradle-to-gate
Simion et al. 2013 (Recycled aggregates from C&D waste)	246	16	Cradle -to-gate
Blengini and Garbarino 2010 (Recycled aggregates from C&D waste)	-250	-14	Cradle-to-site
Butera et al. 2015 (Recycled aggregates from C&D waste)	145	8.73	Cradle-to-site
This study (Recycled aggregates from C&D waste)	211– 235	11–12	Cradle -to-site
This study (Recycled aggregates from waste glass)	156	9	Cradle -to-site

3.6 Summary

Hong Kong generates a significant amount of C&D waste and waste glass, and most of which are disposed of at landfills and public fills. This has created tremendous environmental problems due to the shortage of waste disposal sites in Hong Kong. This study was conducted to assess the environmental impacts of aggregate production from these waste materials, and to compare them with the aggregate production from virgin materials which can be utilized for the production of lower grade concrete products and also in road construction as sub-base materials. The LCA results show that about 49-51% net environmental impacts can be reduced in producing recycled aggregates from C&D waste instead of producing aggregates from crushed stone. In addition, about 185 MJ of non-renewable energy consumption and 14 kg CO_2 eq GHG emissions can be saved (while the net environmental impacts saving is about 59%) in producing 1 t of recycled fine aggregates from waste glass instead of river sand.

The sensitivity analysis result shows that the variation of transport distances up to 20% does not affect the results of the aggregate production from C&D waste significantly (the variation of the net impact is less than 12%), whereas aggregate production from waste glass is more sensitive to the waste collection and transport distances to the aggregate manufacturing site. However, significant environmental gains (about 43-44%) can still be achieved by producing recycled aggregates from both C&D waste and waste glass, even with 20% longer waste collection and transport distances considered.

It is possible to further reduce environmental impacts through the effective design of waste collection and transport system for recycled aggregate production. However, in the waste management policy aspect, recycling of C&D waste and waste glass can substantially save landfill space which is very important for compact cities, like Hong Kong. Moreover, alternative and sustainable sources of aggregates are in demand due to the shortage of natural aggregates throughout the world. Considering the positive aspects identified for recycling of C&D waste and waste glass, it is necessary to strengthen the policy aspects, particularly on the procurement policy of recycled materials to ensure sustainable resource management.

CHAPTER 4

EVALUATION OF ENVIRONMENTAL FRIENDLINESS OF CONCRETE PAVING ECO-BLOCKS

4.1 Introduction

The use of recycled aggregates in various construction activities and products has been gaining interest globally. As the quarrying activities for natural aggregates production are responsible for significant environmental consequences, using recycled aggregates could effectively minimize waste generation. Due to the increase of sustainability concern, the construction industry is now interested in lowering the environmental impacts throughout the products life cycle. Therefore, the industry is now playing an important role in leading to sustainable development through the application of various sustainable tools by assessing the whole life cycle of materials and products (Koroneos and Dompros 2007).

A significant amount of construction and demolition (C&D) wastes are generated each year globally. However, the improper management or even traditional practices of C&D wastes disposal may impose significant environmental impacts. In Hong Kong, C&D waste and waste glass management is a serious concern due to the running out of disposal sites to accommodate a huge amount of wastes generated each year, because currently operated three strategic landfills, namely South East New Territories (SENT), North East New Territories (NENT), and West New Territories (WENT), in Hong Kong will be running out by 2016 and 2018, respectively (HKEB 2011). According to the Hong Kong Environment Protection Department (HKEPD 2015), about 62,392 tpd (tonnes per day) of C&D waste were generated in 2013, of which 95% were disposed as filling materials for land reclamation and 5% were dumped at landfills. In addition, about 353 tpd of waste glass were disposed to landfills in Hong Kong in 2013. The recycling rate of waste glass in Hong Kong was very low (about 17%) compared with other developed countries, such as

Japan (95%), Taiwan (84%), South Korea (70%), EU (68%), Germany (90%), Switzerland (90%), and UK (44%) (HKGPC 2013). In addition, C&D waste and waste glass accounted for 25% and 3.5% of the total municipal solid wastes in 2013, respectively (HKEPD 2015). Due to the non-combustible and non-putrescible nature of C&D waste and waste glass, as well as the running out of the disposal sites, the management of these wastes is a serious concern in cities like Hong Kong. Moreover, many cities like Hong Kong urgently need alternative and sustainable sources of aggregates, as the local quarry sites for aggregate production are expected to be exhausted soon and the import of aggregates is not sustainable. However, C&D waste and waste glass have high potential for recycled aggregate production.

Several efforts have been developed to recycle and reuse C&D waste as construction materials (Cyr et al. 2012). Numerous studies demonstrated that recycled C&D waste aggregates can be used as construction materials for the production of building and paving blocks and pavement flags (Soutsos et al. 2011), concrete kerbs and floor blocks (Gayarre et al. 2013), and concrete paving blocks (Poon et al. 2007). Besides, recycled waste glass is also a potential source of aggregate which can be used for the production of concrete blocks, self-compacting concrete and architectural mortar (Ling et al. 2013; Lee et al. 2013), lightweight concrete (Blengini et al. 2012a), glazes (Andreola et al. 2005), concrete applications with lead extraction (Chen et al. 2009) and without lead extraction (Kim et al. 2009), and cement mortar (Ling and Poon 2012).

Although the above-mentioned studies have justified the use of recycled aggregates (C&D waste and waste glass) as engineering implications towards the environmental sustainability, the associated environmental impacts on the whole life cycle of recycled products unfortunately escaped attention. Hence, a comprehensive life cycle assessment (LCA) was conducted in this research to assess the environmental sustainability of a renowned recycled product, eco-blocks, because LCA is a widely used and accepted means to assess the relative environmental performance of a product or process.

The eco-blocks produced from recycled C&D waste and waste glass have been successfully developed by the authors' research team in Hong Kong. With continuous improvement, the eco-blocks now achieved its advance form, which is the third generation (3G) with upgrading of shape, size, strength, varieties, and mix-proportion of materials. Previous studies mainly focus on mechanical properties of the eco-blocks while the environmental value of the eco-blocks is yet to be quantified. Hence, it is necessary to assess the environmental performance of these eco-blocks in order to be claimed as "eco" or "green" products. Three generations of the eco-blocks, namely "1G," "2G," and "3G," based on two different mix-proportions of the materials, namely "MP 1" and "MP 2," were assessed in this research using LCA techniques (MP 1 is the existing mix-design of eco-blocks which is used by the company for commercial production, whereas MP 2 is the newly design mix-proportions of paving eco-blocks by utilizing more waste materials which is used to investigate and compare the environmental performance within the processes).

The results were then compared with those of the natural blocks manufactured with virgin materials. The environmental feasibility study of the eco-blocks is important not only for green construction but also for reducing primary resource depletion, energy consumption, waste management, and its associated impacts.

4.2 Methodology

The objective of LCA proposed by ISO 14040 standards (ISO 2006) is to evaluate the energy and environmental impacts of a product or process, taking into account its whole life cycle, from the raw material extraction to its final disposal which is included in the LCA methodology. LCA applications are now extensively used for eco-labeling of a product, strategic planning, promotion, consumer education and satisfaction, process development or improvement, and product design throughout the world (Reza et al. 2011). Therefore, the prospect of assessing the environmental performance and gain of products throughout their life cycle through a comprehensive analysis is a big deal of using LCA methodology. LCA consists of four major steps, which are (1) defining goal and scope, (2) creating the life cycle inventory, (3) impact assessment, and (4) results interpretation (Marinkovic et al. 2010).

4.2.1 Composition of the natural blocks and eco-blocks

In Hong Kong, different types of eco-blocks are currently produced using various locally generated waste materials, such as recycled C&D waste and waste glass. The data regarding the mix-proportion of eco-blocks production were collected from a eco-block manufacturer in Hong Kong, which is given in Table 4-1. The aggregates: binder ratio was 5:1 and 4:1 for normal blocks and eco-blocks, respectively.

Table 4-1 – Mix-proportions for paving blocks production in Hong Kong (by weight)

Name of block	Processes	Natural fine (river sand; %)	Natural coarse (crushed stone; %)	Natural fine (crushed stone; %)	Recycled fine (waste glass; %)	Recycled coarse (C&D waste; %)	Recycled fine (C&D waste; %)	*Amount of aggregates (%)*	Cement (%)	Fly ash (%)	Pigment (%)	Admixture (%)	TiO_2 (%)	*Amount of other materials (%)*
NB	MP 1	50	30	20	--	--	--	*80*	100	--	[a] 2-6	[a] 0.5-1	--	*20*
	MP 2	45	30	25	--	--	--	*80*	100	--	[a] 2-6	[a] 0.5-1	--	*20*
1G EB	MP 1	50	15	--	--	15	20	*75*	75	25	[a] 2-6	[a] 0.5-1	--	*25*
	MP 2	35	15	--	--	15	35	*75*	75	25	[a] 2-6	[a] 0.5-1	--	*25*
2G EB	MP 1	25	15	--	25	15	20	*75*	75	25	[a] 2-6	[a] 0.5-1	--	*25*
	MP 2	10	10	--	25	10	45	*75*	75	25	[a] 2-6	[a] 0.5-1	--	*25*
3G EB	MP 1	25	15	--	25	15	20	*75*	75	25	[a] 2-6	[a] 0.5-1	[a] 0.5-1	*25*
	MP 2	10	10	--	25	10	45	*75*	75	25	[a] 2-6	[a] 0.5-1	[a] 0.5-1	*25*

[a] by the weight of cement; NB, Normal blocks; 1G EB, 1st generation eco-blocks; 2G EB, 2nd generation eco-blocks; 3G EB, 3rd generation eco-blocks; MP 1, Manufacturing process 1; MP 2, manufacturing process 2

4.2.2 System boundary and functional unit

Since various types of materials are used for the manufacturing of the concrete paving blocks, it is important to use the same material proportion to keep the inventory data consistent. Therefore, the inventory has been conducted for the production of recycled aggregates (C&D waste and waste glass) and natural aggregates (mainly imported from mainland China) production and transport to Hong Kong separately. Then, each material has been used in the production of 1 t of blocks according to their mix-proportion. Due to the structural and other properties of both types of paving blocks were almost similar, 1 t of paving blocks as functional unit was considered in this study. Based on the guidelines provided by ISO 14040 (ISO 2006), "cradle-to-site" system boundary was selected in this study which includes the production and collection of raw materials, blocks manufacturing, and finally, transport to the user sites. Eco-blocks are now commonly used in Hong Kong, and no special requirement is needed for maintenance during the use phase/service life. Therefore, the study considers the cradle-to-site system boundary for both the natural blocks and the eco-blocks as the "site-to-grave" aspect is similar for the both types of blocks. In addition, the expected service life of the eco-blocks is similar as for natural blocks (e.g. 50 years). However, the use phase for the 3G eco-blocks is slightly different from the other blocks which will be briefly described at the results and discussion section.

4.2.3 Data collection and impacts assessment methodology

A comprehensive LCA is needed to assess environmental impacts of concrete paving blocks. The principal material is the aggregates for the concrete blocks. In Hong Kong, more than 75% of all the primary aggregates are imported from Dongguan and Panyu in Guangdong province in mainland China. Therefore, the necessary information related to the materials, energy, and fuels for producing natural aggregates and also their transport to Hong Kong were collected from the respective manufacturers and local suppliers. In addition, the required data for producing recycled aggregates were collected from recycled aggregate producers in Hong Kong as first-hand data. The avoided impacts of disposing an equivalent amount of C&D waste and waste glass at landfills, and also the production of the same amount of aggregates from virgin sources were considered in this study.

Since many of the emission data (upstream data) related to fuel production and consumption, electricity production, and material transportation could not be collected as first hand, data provided by the China Light and Power (CLP) and the Chinese Life Cycle Database (CLCD) were used for some of the materials and processes to fill up the data gaps. The CLCD database contains the life cycle inventory (LCI) data for Chinese materials and processes. As the majority of the materials in Hong Kong come from (and are produced in) mainland China, the use of the CLCD database would be more appropriate than other LCI databases. However, other references and LCI databases were also used when CLCD does not provide such LCI data for some materials and processes (Table 4-3). Finally, LCI data of the downstream process, e.g. block manufacturing and transport to the user sites, were collected from a eco-block manufacturer as first-hand data.

To assess environmental impacts, a mid-point/damage approach was selected in this study. Based on the importance and priority for Hong Kong, seven mid-point impact indicators were selected and then assessed by the IMPACT 2002+ impact method. The selected mid-point and damage indicators with their units are shown in Figure 4-1 (Jolliet et al. 2003).

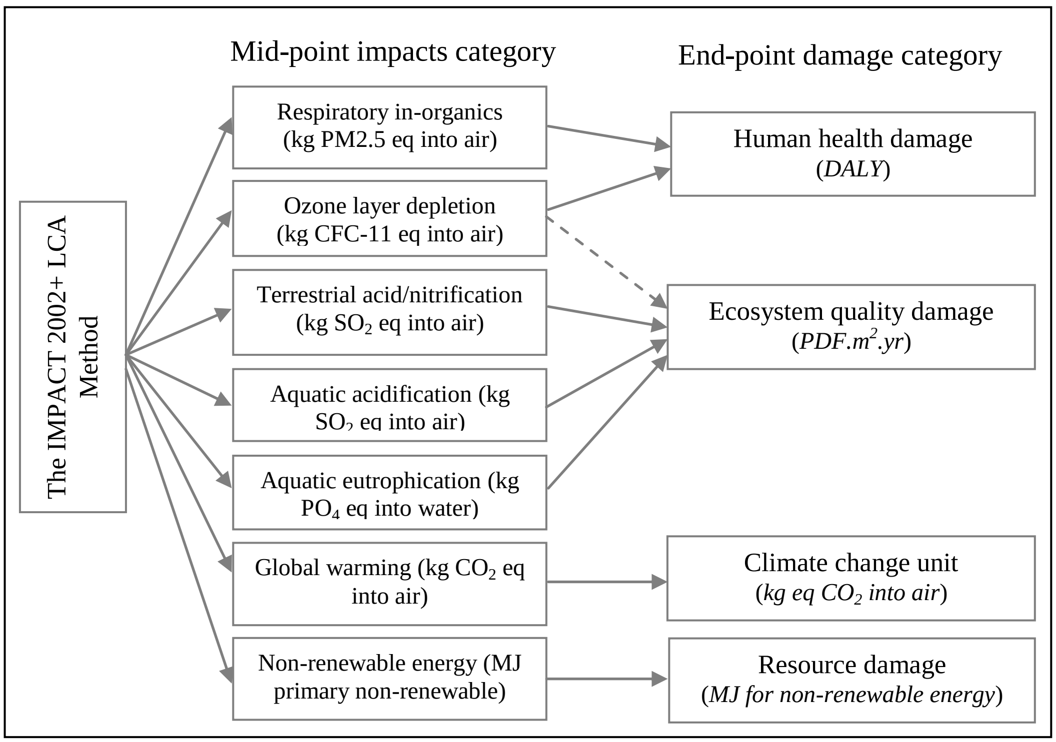


Figure 4-1 - Selected environmental impact indicators based on the IMPACT 2002+ Method

4.2.4 Sensitivity analysis

The LCA result does not represent the precise data, as it may be affected by various uncertainties (Beccali et al. 2010). However, sensitivity analysis helps to verify the validity of the collected data and the scientific assumptions of the model. Bjorklund (2002) have identified several factors as the uncertainty of LCA results, such as parameter and model uncertainty, uncertainty due to choices, spatial and temporal variability, and variability between sources and objects. Therefore, it is important to clearly distinguish the variability in LCA results from uncertainty (Stratton et al. 2011). Uncertainty combined with the sensitivity analysis has led to an increase in the confidence in the LCA outcomes (Guo and Murphy 2012) and also increase the reliability, transparent, and representative of LCA results (Cellura et al. 2011). Therefore, this study conducted a sensitivity analysis to analyze the influence of input parameters on the LCA outcomes by calculating different scenarios suggested by Bjorklund (2002).

4.3 Description of the paving block production processes

This section provides the information on the data and assumptions that have been taken to make the LCA model within the chosen cradle-to-site system boundary. In LCA studies, some logical assumptions are coherently needed as it is almost impossible to model a product by strictly following the real process step by step (Blengini et al. 2012b). For example, the distance for transporting the blocks to the use sites was calculated based on the average distance from several user sites. Therefore, the study assumed that the average transport distance would not change too much, as Hong Kong is a small city. The life cycle inventory (LCI) data including transport information on materials and the energy requirements for aggregates production are summarized in Tables 4-2 and 4-3. A brief description of the production processes of natural blocks and eco-blocks is provided below.

Table 4-2 - Materials and transport for paving blocks production in Hong Kong

Materials	Transported from	Transport type (t)	Distance (km)
Natural aggregates	Guangdong Province, China	Inland barge; trucks (30)	20-50; 128; 6
Cement	Green Island Cement (local)	Trucks (30)	5
TiO_2	Germany	Ocean ship; trucks (18)	18675; 6
Admixture	Guangzhou, China	Trucks (18)	170
Pigment	Guangzhou, China	Trucks (18)	170
Fly ash (recycled)	CLP power plant (local)	Trucks (30)	5
Fly ash (landfill)	CLP power plant (local)	Trucks (30)	7
C&D waste (recycled)	Variable [a]	Trucks (30)	45
C&D waste (landfill)	Variable [a]	Trucks (30)	35
Waste glass (recycled)	Variable [a]	Trucks (18)	55
Waste glass (landfill)	Variable [a]	Trucks (6); trucks (30)	6; 35
Packaging wood	Guangdong Province, China	Trucks (30)	180
Paving blocks transport to user site	Manufacturing site (local)	Trucks (30)	41

[a] The distance is variable due to different geographic locations (the average distance is considered)

Table 4-3 - Energy requirements for materials/processes and used databases

Materials/processes	Energy requirement	Upstream data source
Natural fine (river sand)	68 MJ/t (diesel)	CLCD 2010d
Natural fine (crushed stone)	27 MJ/t (electricity) and 50 MJ/t (diesel)	CLP 2014; CLCD 2010c,d
Natural coarse (crushed stone)	22 MJ/t (electricity) and 50 MJ/t (diesel)	CLP 2014; CLCD 2010c,d
Recycled fine (C&D waste)	11 MJ/t (electricity) and 61 MJ/t (diesel)	CLP 2014; CLCD 2010c,d
Recycled coarse (C&D waste)	4 MJ/t (electricity) and 70 MJ/t (diesel)	CLP 2014; CLCD 2010c,d
Recycled fine (waste glass)	47 MJ/t (electricity) and 21 MJ/t (diesel)	CLP 2014; CLCD 2010c,d
Landfill of waste materials (C&D waste and Waste glass)	R [a]	ELCD 2013
Cement production	R [a]	Zhang et al. 2014; CLCD 2010b
Fly ash (processing)	34 MJ/t (electricity) [b]	CLP 2014; CLCD 2010c
TiO_2 production	R [a]	Ecoinvent 3.0 2013h
Admixture production	R [a]	EFCA 2002; Sjunnesson 2005
Pigment production	R [a]	CPM LCA 2014
Packaging wood production	R [a]	USLCI 2012c
Block making process	110 MJ/t blocks (electricity)	CLP 2014; CLCD 2010c
On-site handling	8 MJ/t blocks (diesel)	CLCD 2010d
Transport, road	R [a]	CLCD 2010e
Transport, sea (Inland barge)	R [a]	CLCD 2010a
Transport, sea (Ocean ship)	R [a]	Ecoinvent 3.0 2013i

CLCD, The Chinese core Life cycle Database; CLP, The China Lighting and Power; ELCD, European reference Life Cycle Database; EFCA, European Federation of Concrete Admixture Associations; CPM LCA, Center for Environmental Assessment of Product and Material Systems- Life cycle Assessment Database; USLCI, U.S. Life Cycle Inventory Database; R [a], Referring to the databases mentioned in the Table 4-3, [b] MPA 2009

4.3.1 Natural block production

The system boundary and processes of natural paving blocks production are given in Figure 4-2. For producing natural blocks, some of the raw materials are locally produced and others are imported. The natural fine aggregates (e.g. river sand, crushed stone) and coarse aggregate (e.g. crushed stone) are used for paving blocks production. Therefore, the extraction/excavation of materials, processing (e.g. crushing and screening), on-site handling and transport, transport to Hong Kong, and finally to blocks production site have been considered in this study.

Cement is an important component for paving blocks production. The LCI data for cement production have been collected from the CLCD database and Zhang et al. (2014). Another two constitutes of blocks production are pigments and admixtures which are imported from Guangzhou, China. The LCI data for pigments are not available in the CLCD database and software libraries; hence, the LCI data for iron oxide (collected from CPM LCA database) are used as the substitute of pigments (because the iron oxide is the major component of pigments). There are several options to fill up the LCI data gap in the LCA study. The first option is the inter-process flows for which data are lacking can be estimated by using information for the most similar “analogous” process or product for which data are available. The second option is to replace with the main ingredients of the product (Huijbregts et al. 2001**)**. Therefore, the study used the second option to fill data gap for pigments, because the main ingredients or the major processes are mainly caused for most of the impacts of a product. The LCI data for the admixtures (e.g. super-plasticizer) used was collected from the European Federation of Concrete Admixtures (EFCA 2002) and Sjunnesson (2005).

After that, the block is manufactured using the block-making machine, and the finished block is handled by various conveyers. The energy consumption during block-making process including conveyer handling and block packaging has been accounted in the study. According to the mix-proportions, a certain amount of water is used for block-making process. The energy consumption due to running the water pump has also been accounted for. Then, the block is packaged with wooded frame (about 8.0123 kg wooded frame is needed to package per tonne paving blocks) and clear thin polythene (the amount of polythene used is very small; thus, it is excluded from the system boundary). The wood lumber is imported from Guangdong province in mainland China. The LCI data for wood lumber production have been used from the software libraries. Finally, the ready blocks are transported to the user sites, and the average transport distance (collected from block manufacturer) has been accounted in the study. Therefore, the energy related to the transport is taken into accounted for the model.

4.3.2 Eco-block production

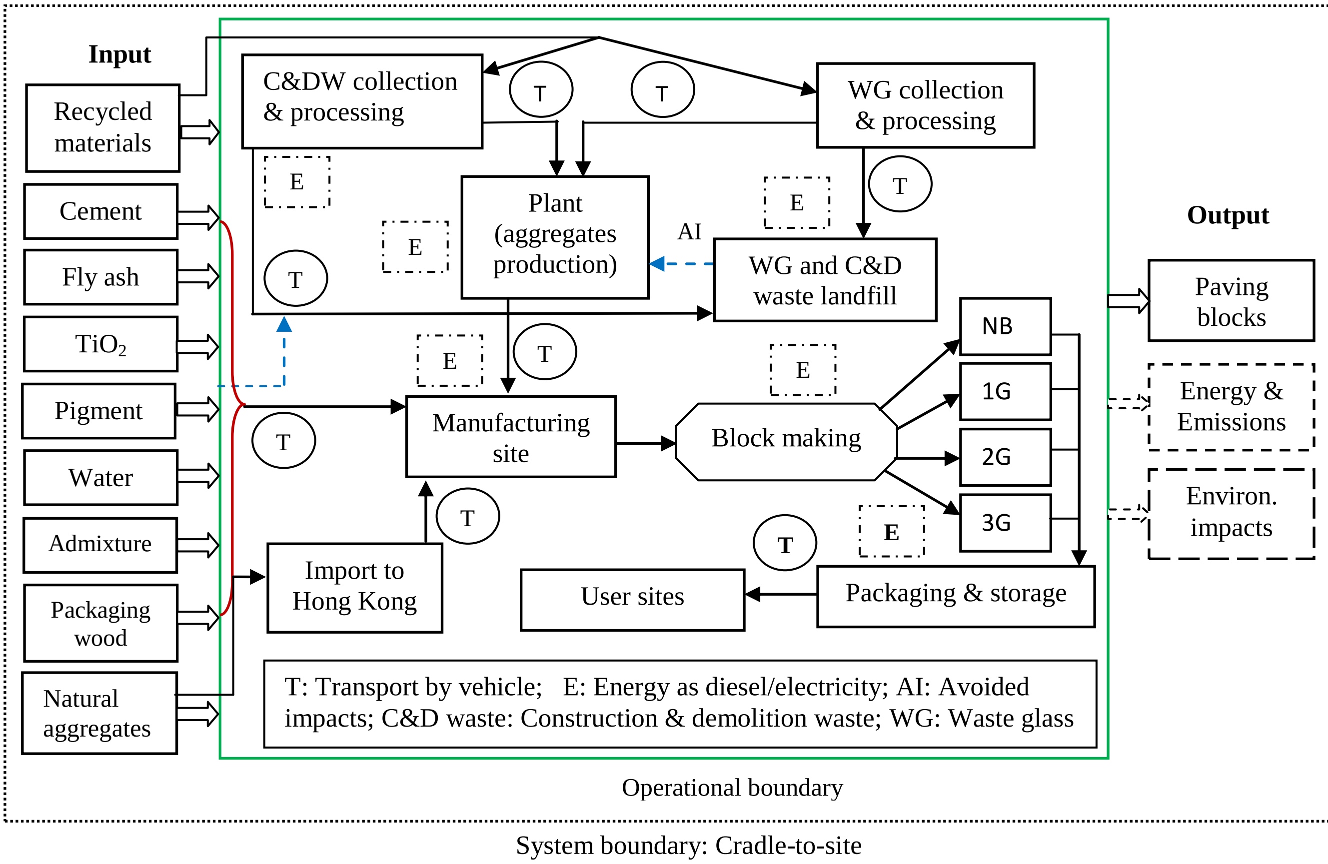
The system boundary and processes of eco-blocks production are shown in Figure 4-2. The mix-proportion of eco-block (1G, 2G, and 3G) production is also presented in Table 4-1. Natural aggregates are partially replaced (35-50% of the total aggregates) with recycled aggregates to produce 1G eco-blocks. All steps related to the production of recycled aggregate from C&D waste are included in the study which include on-site sorting, transport to processing site, recycled aggregate processing, and also transport to landfills (for including avoided impacts). In addition, the study also considered all the possible ways of waste glass recycling in Hong Kong, and the collection, transport to processing site, and waste glass processing are considered in this LCA. After received by the plant, recycled waste glass goes through several processing stages such as shredded and milling to make fine aggregates. Similar as C&D waste, the environmental impacts of landfilling of waste glass are considered as avoided impacts.

Apart from the other materials used in the natural blocks (e.g. cement, water and pigment), fly ash is used as a partial replacement of cement (25% of the cement content) to produce the 1G eco-blocks. Until now, fly ash is considered as a waste material by many studies, whether they mentioned it as industrial waste (Habert and Roussel 2009) or by-product (Turk et al. 2015; Zhang et al. 2014; Chowdhury et al. 2010; Flower and Sanjayan 2007). In this study, fly ash is considered as a waste material produced by a coal-fired power plant, the avoided impacts due to fly ash landfilling is also considered. However, the processing and then transport from CLP Hong Kong power plant to block manufacturing site and to landfill sites is accounted as induced impacts, and as avoided impacts, respectively. In Hong Kong, most of the fly ash produced in local power plant is resourcefully utilized, and rest of the demand is fulfilled by importing mainly from mainland China.

For the production of 2G eco-blocks (Table 4-1), natural aggregates are significantly replaced (60-80% of the total aggregates) with recycled aggregates such as from C&D waste and waste glass. In addition to aggregates, other materials such as cement, pigment, water (as described in the natural block production), and fly ash (as described for 1G eco-block production) are also used for producing 2G eco-block.

As a part of the continuous development of eco-blocks, the authors' research team developed the air pollutant removal and self-cleaning paving eco-blocks which are known as the third generation eco-blocks "3G EB." Apart from the other materials used in the 2G eco-block production, titanium dioxide (TiO_2) is used as air cleaning agent in the 3G eco-block (Table 4-1), which can remove a significant amount of NO_x pollutants from the local air. In Hong Kong, TiO_2 is imported from Germany. Therefore, the transport distance for importing TiO_2 to Hong Kong port and then to block manufacturing site is accounted and modeled in this study. Recently, the use of photocatalyst in the construction field has gained increasing attention. This is mainly due to the air-purification, self-cleaning, and bacteria inactivation potential of the photocatalytic process (Guo et al. 2012). Nano-TiO_2 can degrade organic and inorganic air pollutants by the photocatalytic process, especially nitrogen oxides (NO_x) from the local air (Chen and Poon 2009). The 3G eco-blocks were produced with the incorporation of a small amount of nano-TiO_2, which can degrade a certain amount NO_x during their service life by TiO_2-assisted photocatalysis under solar UV-A irradiation. According to Guo and Poon (2013), the NO_x removal rates of 3G eco-blocks was 2.8-4.9 mg h^{-1} m^{-2} depending on the use of different types of recycled glass aggregate (20-100% replacement of sand by glass aggregates). According to the eco-block manufacturer, the 3G eco-blocks can reduce NO_x concentration by at least 20% at laboratory conditions.

All the materials and their production, transport to block production sites, block making, packaging, and then transport to user sites are modeled and assessed using SimaPro 8.0.1 software. SimaPro is one of the most widely used and accepted LCA tools. It helps to model various products and processes comprehensively and analyzes the results interactively for achieving sustainability goals (PRé Consultants 2014).



NB, Natural blocks; 1G, 1st generation eco-blocks; 2G, 2nd generation eco-blocks; 3G, 3rd generation eco-blocks

Figure 4-2 - Process map of concrete paving block production with the cradle-to-site system boundary

4.4 Results and discussion

Environmental impacts for producing three generations of eco-blocks and natural blocks have been assessed and compared by LCA technique. Impacts evaluation and comparison between the two manufacturing scenarios (MP 1 and MP 2 according to the mix-proportion mentioned in the Table 4-1) was also carried out with selected functional unit.

4.4.1 Environmental impacts of concrete paving blocks production

Within the system boundary of the study, the aggregated results of the selected mid-point environmental impact indicators for producing 1 t of paving blocks are shown in Table 4-4. It is estimated that about 2068 - 2083 MJ of non-renewable energy is needed to produce and transport 1 t of natural blocks to user sites, while 1442-15115 MJ, 1313-1416 MJ and 1422-1525 MJ are needed for 1G eco-blocks, 2G eco-blocks, and 3G eco-blocks, respectively.

The contribution to non-renewable energy consumption and greenhouse gases emissions by different materials and processes for different types of paving blocks production is shown in Table 4-5 (manufacturing process 1). For natural blocks production, cement is the highest energy consumer (50.6%), whereas the energy consumptions for aggregates, pigment, admixture, block manufacturing process, and transporting to user sites are 12.54%, 3.27%, 9.23%, 17.3%, and 7.06%, respectively. Similarly, more than three quarters of the CO_2 eq greenhouse gases (GHG) emissions are associated with the cement (76.8%), whereas 6.85%, 4.09%, 7.63%, 3.63%, and 1% of the CO_2 eq GHG emissions are related to aggregates, admixture, manufacturing process, transporting to user site, and others, respectively.

For 1G eco-blocks production, about 60.63% of energy is associated with cement, whereas 4.76%, 3.51%, 3.11%, 22.4%, and 9.15% are attributed to natural aggregates, admixture, pigment, block production, and transporting to user site, respectively. In addition, a certain amount of natural aggregates are replaced by recycled aggregates, and hence, it could minimize and save the natural aggregate production and transport related energy with recycling and production energy itself by avoiding the landfill associated energy. Based on the mix-proportion of the 1G eco-block, certain amounts of cement are replaced by fly ash. As fly ash is a waste material, and its application as the cement substitute of certain percentage greatly reduced energy requirements. In total, fly ash and recycled aggregates reduce 5.22 and 21.55% of the total energy consumption for producing 1G eco-blocks, respectively, compared to the natural blocks. Similarly, about 83.2% of the CO_2 eq GHGs is emitted only for cement, and 9.15%, 2.4%, 1.46%, 4.3%, and 1% GHGs are released for production process, natural aggregates, admixture, transporting to user sites, and others, respectively. However, fly ash and recycled aggregates reduce 8% and 9% of the total GHGs emission for producing 1G eco-blocks, respectively, compared to the natural blocks.

For the production of 2G eco-blocks, about 63.39% of energy is required for cement, while the energy requirements for manufacturing process, natural aggregates, transporting to user sites, admixture, and pigment are 23.53%, 6.15%, 10.18%, 3.99%, and 3.54%, respectively. Based on the mix-proportion for 2G eco-block production, a certain percentage of natural aggregates are replaced by recycled aggregates (such as C&D waste and waste glass), and a considerable amount of cement are replaced by fly ash. Hence, 23.82% and 7.7% of the total energy consumption are avoided due to the use of recycled aggregates from C&D waste and waste glass, and fly ash, respectively, compared to the natural blocks. Similarly, about 85.8% of the total GHGs emissions are associated with cement, while 9.38%, 2.96%, 4.46%, 1.51%, and 1% are closely related to manufacturing process, natural aggregates, transporting to user site, admixture, and others, respectively. About 10% of the total GHGs emission is avoided due to the use of recycled aggregates from C&D waste and waste glass, and about 9.85% of the total GHGs emission is reduced because of the use of fly ash, compared to the natural blocks.

A small amount of photocatalyst, TiO_2, has been used to produce 3G eco-blocks. Other materials and mix-proportions are the same as those of 2G eco-blocks. It can be seen that the production of 3G eco-blocks consumes 7% higher energy and emits 3.58% higher GHGs than the 2G eco-blocks. The reason behind the higher energy consumption and GHGs emission for 3G eco-blocks is attributed to the use of TiO_2, as TiO_2 is considered as a high energy and GHGs intensive material. However, TiO_2 is able to significantly reduce the NO_x concentration from the air, which is not accounted in this study, as the system boundary of the study is cradle-to-site which means it does not consider the use phase of paving blocks.

Similar to the energy consumption and GHGs emission, a significant amount of other impact indicators (e.g. respiratory inorganics, ozone layer depletion, acidification potential, and eutrophication) can be reduced by adoption of recycled aggregates from C&D waste and waste glass and fly ash instead of a certain amount of natural aggregates and cement (Table 4-4 and Figure 4-3).

Table 4-4 - Summative environmental impacts of paving eco-blocks

Mid-point impacts category	Natural blocks		1G Eco-blocks		2G Eco-blocks		3G Eco-blocks	
	MP 1	***MP 2***	***MP 1***	***MP 2***	***MP 1***	***MP 2***	***MP 1***	***MP 2***
Respiratory inorganics (kg PM2.5 eq)	0.20	0.20	0.16	0.15	0.15	0.14	0.16	0.15
Ozone layer depletion (kg CFC-11 eq)	1.21E-06	1.21E-06	7.05E-07	5.5E-07	-2.2E-07	-2.4E-06	-1.3E-07	-1.5E-06
Acidification potential (kg SO_2 eq)	4.74	4.76	3.66	3.46	3.36	3.09	3.70	3.43
Aquatic eutrophication (kg PO_4 P-lim.)	0.002	0.002	-0.069	-0.099	-0.119	-0.159	-0.117	-0.157
Global warming potential (kg CO_2 eq)	261	262	217	212	210	203	217	211
Non-renewable energy consumption (MJ primary)	2068	2083	1515	1442	1416	1313	1525	1422

Table 4-5 - Contribution analysis

Contributors	Natural blocks		1G eco-blocks		2G eco-blocks		3G eco-blocks	
	GWP (%)	*NRE (%)*	*GWP (%)*	*NRE (%)*	*GWP (%)*	*NRE (%)*	*GWP (%)*	*NRE (%)*
Cement	76.80	50.60	83.20	60.63	85.80	63.39	82.03	62.41
Natural aggregates	6.85	12.54	2.40	4.76	2.96	6.15	2.85	6.10
Admixture	4.09	9.23	1.46	3.51	1.51	3.99	1.45	3.56
Pigment	1.00	3.27	0.88	3.11	0.91	3.54	0.98	3.15
Block manufacturing process	7.63	17.30	9.15	22.4	9.38	23.53	9.03	20.34
Transporting to user sites	3.63	7.06	4.30	9.15	4.46	10.18	4.36	8.11
Fly ash			-0.21	-0.74	-0.17	-0.80	-0.18	-0.76
Recycled aggregates			-1.18	-2.82	-4.85	-9.98	-4.68	-9.90
TiO_2							4.16	6.99
Total	100	100	100	100	100	100	100	100

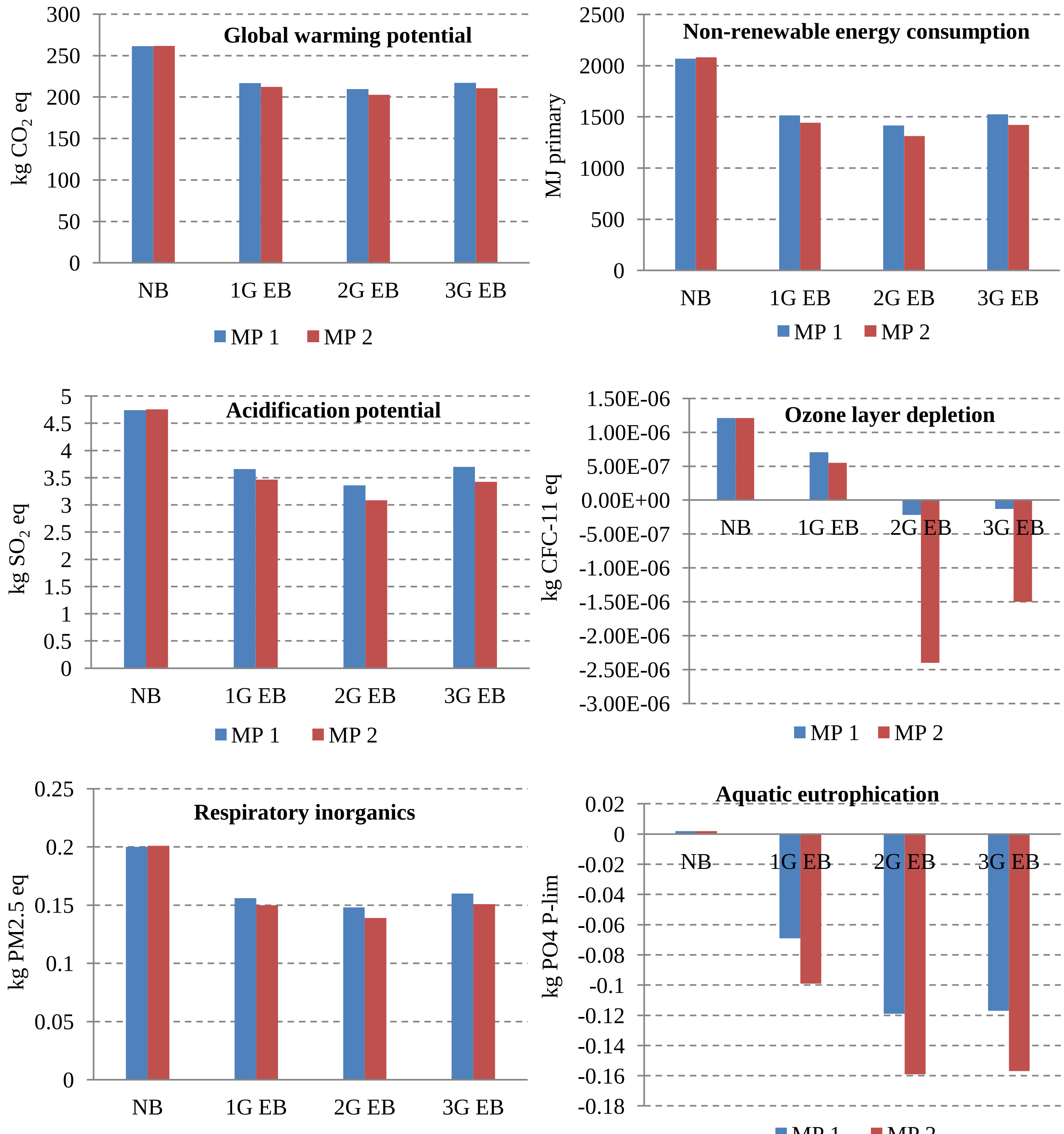
GWP, Global warming potential; NRE, Non-renewable energy

4.4.2 Environmental impacts comparison of paving blocks

The LCA results showed that based on the MP 1, about 261, 217, 210, and 217 kg CO_2 eq GHGs were emitted for producing 1 t of natural blocks (NB), 1G eco-blocks, 2G eco-blocks, and 3G eco-blocks, respectively. The figures indicated that in comparison with NB production, about 17, 20, and 17% lower GHGs were emitted for producing 1G, 2G, and 3G eco-blocks, respectively. Similarly, about 19, 23, and 20% lower GHGs emission were observed in the 1G, 2G, and 3G eco-blocks, respectively, than in the NB based on the MP 2. The results for both processes indicated that eco-blocks reduced climate change effects significantly. Similarly, about 27, 32, and 26% lower energy were consumed for producing 1G, 2G, and 3G eco-blocks, respectively, than producing NB for the process MP 1, while 31, 37, and 32% , respectively, for the process MP 2.

The emission of PM 2.5 eq for the effects of respiratory damage, about 22, 26, and 20% lower impacts are observed for producing 1G, 2G, and 3G eco-blocks, respectively, compared with the natural blocks for the process MP 1. Similarly, their corresponding reductions in CFC-11 eq emitted as ozone layer depletion effects are about 41.7, 118, and 110.75%, respectively. In addition, about 4.74, 3.66, 3.36, and 3.70 kg SO_2 eq are emitted as acidification potential for producing normal block, 1G, 2G, and 3G eco-blocks, respectively, resulting in corresponding reductions of about 22.81, 29.14, and 21.96% SO_2 eq emission (MP 1), and it is about 27.31, 35.08, and 27.94%, respectively for the MP 2. Similarly, high savings of eutrophication effects (PO_4 eq) are found for producing the three generations of eco-blocks compared with the natural blocks for both the processes. For the considered impact categories, higher impacts are associated with natural aggregates production due to their higher transport distance. Therefore, higher impacts was observed for the natural blocks, whereas fly ash reduces a significant amount of the total impacts for all eco-blocks compared to the natural blocks, and very high saving is found for using recycled aggregates in the eco-blocks not only due to the avoided impacts but also the lower transport distances for waste collection and recycled aggregates to the block production sites.

Relatively higher other emissions (e.g. CO_2 eq) and energy consumption is associated with 3G eco-blocks compared to the 2G eco-blocks due to the use of TiO_2, compared to 2G eco-blocks due to the uuse of TiO_2 (Table 4-4). However, the benefits regarding the NOx removal activity of 3G eco-blocks was not considered in this study, as “cradle-to-site” system boundary is considered. Overall, the 2G eco-blocks have the lowest environmental impacts for all impacts categories for both of the processes. In addition, among most of the impacts categories, the MP 2 has lower impacts than the MP 1 (Figure 4-3).



[NB, Normal blocks; 1G EB, 1st generation eco-blocks; 2G EB, 2nd generation eco-blocks; 3G EB, 3rd generation eco-blocks; MP 1, Manufacturing process 1, MP 2, Manufacturing process 2]

Figure 4-3 - Impacts comparison among different types of blocks and between the processes

4.4.3 Impacts interpretation

According to the IMPACT 2002+ method, there are four end-point indicators for damage assessment, namely human health, ecosystem quality, climate change, and resources. These end-point indicators are accumulated from all the mid-point indicators. The comparative damage assessment of paving block production for both processes is shown in Figure 4-4. The Figure indicated that in comparison with the natural blocks for the MP 1, 1G eco-blocks, 2G eco-blocks, and 3G eco-blocks exclusively induced lower damages to all the categories analyzed. For producing eco-blocks based on the MP 2, higher savings are observed for all types of eco-blocks than the MP 1.

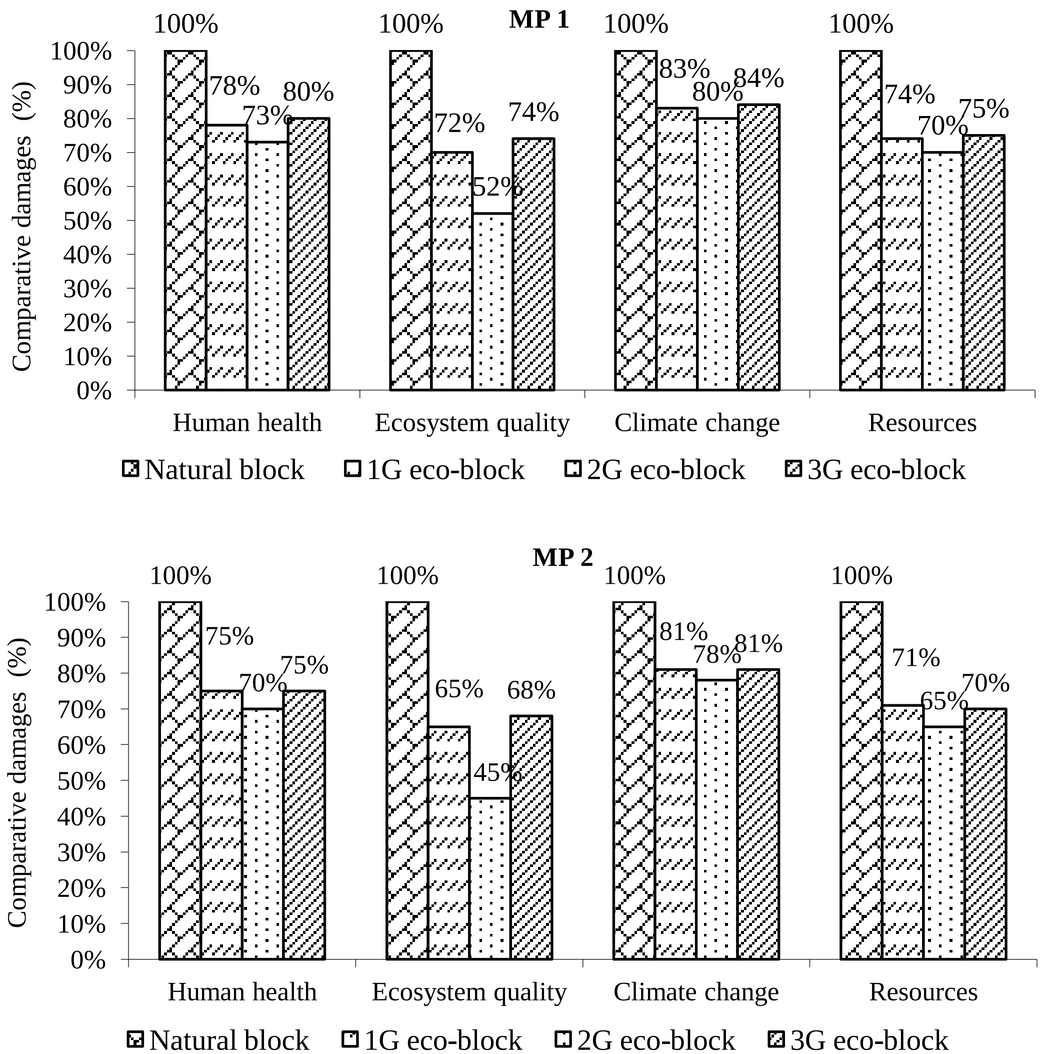


Figure 4-4 - Comparison of damages to different categories of paving blocks

According to the standards for concrete paving blocks provided by the Government of Hong Kong, the compressive strength of paving blocks should not be lower than 35 MPa for use in footways and cycle tracks, whereas it should be more than 45 MPa for use in carriageways and paved areas for vehicular access. In addition, the water absorption value should not be more than 6% tested by a 24-h cold immersion method (ETWB 2004). Numerous studies have been conducted on the structural properties of paving blocks manufactured by natural and recycled aggregate blocks in Hong Kong. All of the studies have confirmed that eco-blocks met the standards given by the Government. However, the compressive strength of natural blocks is slightly higher (about 10%) than that of the eco-blocks, and the water absorption value of eco-blocks is slightly higher (about 10%) than that of the natural blocks due to the use of recycled aggregates (Poon et al. 2002; Lam et al. 2007).

For manufacturing process 2, the experimental result showed that the natural blocks and all types of eco-blocks met the standard of mechanical strength stipulated by the Government. The average compressive strengths of natural blocks, 1G eco-blocks, 2G eco-blocks, and 3G eco-blocks were 53.61, 46.88, 48.66, and 48.57 MPa, respectively, after 28 days of casting.

For producing 2nd and 3rd generation concrete paving eco-blocks, a certain amount of fine aggregates derived from recycled glass (glass cullet) is used. According to Lam et al. (2007), the incorporation of 25% or less recycled glass aggregate induced negligible alkali silica reaction (ASR) expansion in the paving blocks. However, the study recommended that using about 10% of FA (by weight of total aggregate) was needed to control the ASR expansion when the glass aggregate was 25% or higher.

4.4.4 Sensitivity analysis

The results of this study are significantly influenced by the cement, because about 51-63% of the total energy consumption and 77-86% of the total GHGs emission for concrete blocks production are associated with cement. Therefore, a sensitivity analysis is important to estimate the effects on uncertainty and strengthen the reliability of the obtained results due to the different LCI input data for cement. This study conducted a sensitivity analysis in order to assess the effects on the two important impact indicators, e.g. GHGs emission as global warming potential (GWP) and cumulative energy consumption using following scenarios;

Base scenario: LCI data for cement production has been collected from Zhang et al. (2014).

Scenario 1: LCI data for cement has been collected from CLCD database (CLCD 2010b).

Scenario 2: LCI data for cement has been collected from Ecoinvent 3.0 database (Ecoinvent 2013a).

The performed sensitivity analysis showed quite different variations in the GWP of the assessed products (Figure 4-5). The results revealed that GWP can vary from 208.75 kg CO_2 eq (scenario 1) to 243.19 kg CO_2 eq (scenario 2) with 261.45 kg CO_2 eq (base scenario) for the normal block production based on the MP 1. From the base scenario, the change in the GWP varied from - 6.98% (Scenario 2) to - 20.25% (Scenario 1). A similar variation was found for the MP 2.

The variation of GWP for 1G eco-blocks was found to be lowest - 7.31% (Scenario 2) to highest - 23.13% (scenario 1) from the base scenario. For 2G eco-blocks, it was about - 7.49% (scenario 2) to highest - 24.16% (scenario 1). The variation for 3G eco-blocks was ranging from - 7.47% (scenario 2) to - 23.22% (scenario 1) from the base scenario.

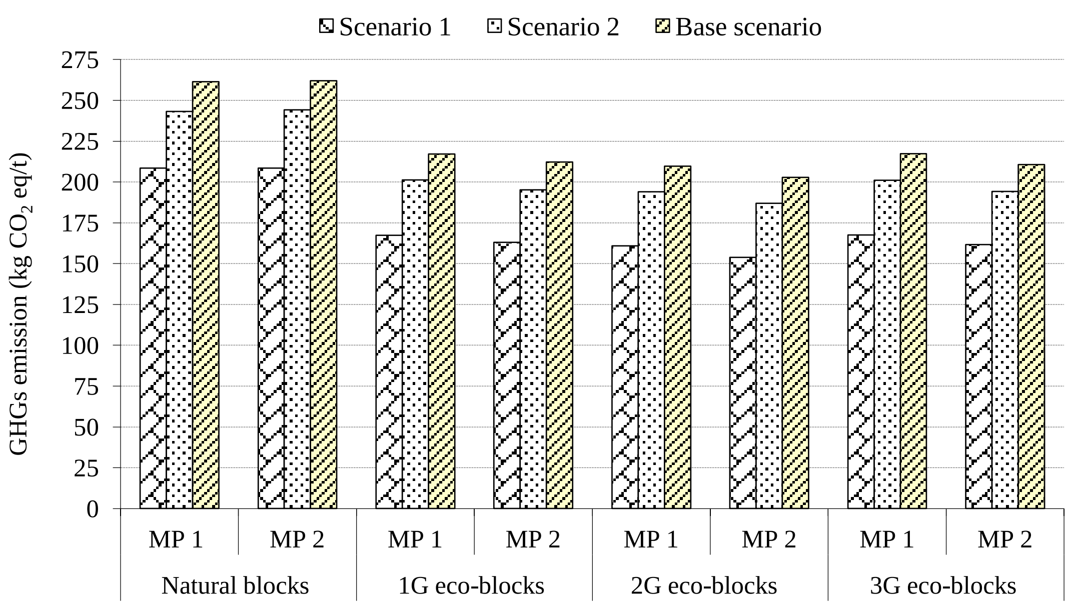


Figure 4-5 - Comparison of GHG emissions at different scenarios

However, the variation is quite low when GWP saving is considered for producing eco-blocks than the natural blocks (Table 4-6). For example, about 17% (base scenario) lower GWP emission is found for producing 1G eco-blocks based the MP 1, whereas for scenario 2 and scenario 1, the reductions are 17.29% and 19.77%, respectively. Therefore, the variation of GWP saving is lower than 4% for all the eco-blocks in all scenarios.

Table 4-6 - Comparison of GHG saving of eco-blocks with natural blocks

Name of block	Processes	Scenario 1 (%)	Scenario 2 (%)	Base scenario (%)	Variation (%)
1G eco-blocks	MP 1	19.77	17.29	17.00	0.29-2.77
	MP 2	21.80	20.10	19.00	1.10-2.80
2G eco-blocks	MP 1	22.83	20.28	19.85	0.43-2.98
	MP 2	26.27	23.45	22.60	0.85-3.67
3G eco-blocks	MP 1	19.71	17.31	16.87	0.44-2.84
	MP 2	22.44	20.47	19.56	0.91-2.88

The results of sensitivity analysis showed quite similar variations in the total energy consumption of the assessed paving blocks (Figure 4-6). The variation was ranging from +4.04% to - 5.61% for natural blocks, +4.64% to - 7.56% for 1G eco-blocks, +5.08% to - 8.30% for 2G eco-blocks, and +4.66% to -7.69% for 3G eco-blocks production for both processes. This indicated that cement also significantly affected the total energy consumption for the manufacturing of paving blocks.

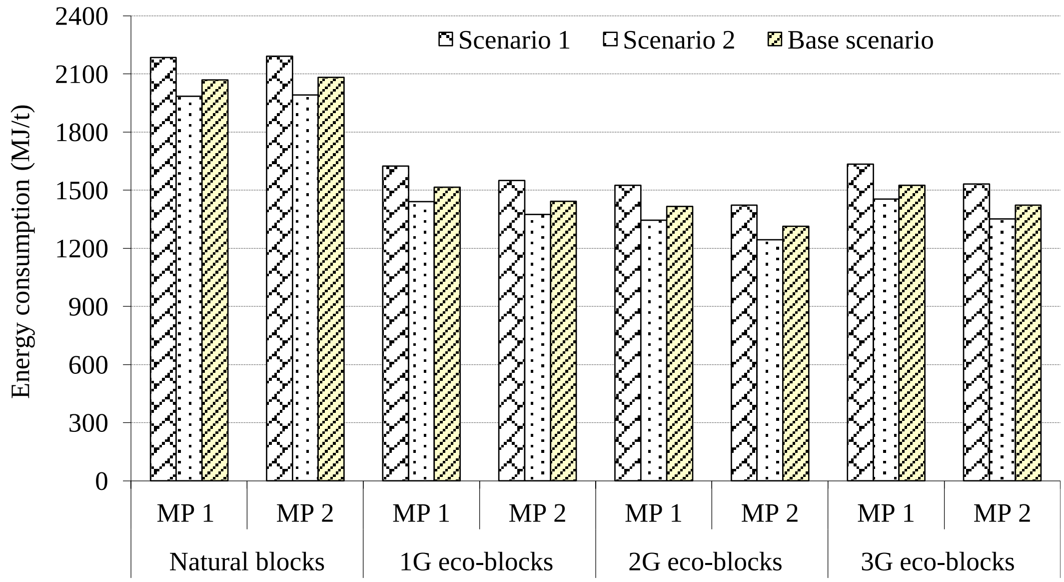


Figure 4-6 - Comparison of total energy consumption at different scenarios

However, when the total energy consumption saving of producing the eco-blocks is compared with that of producing the natural blocks, the variations are significantly low (Table 4-7). The variation of energy saving for different eco-blocks from the natural blocks is ranging from 0.20% to 1.84%, which indicates the LCI data for cement is valid and the obtained results are reliable.

Table 4-7 - Comparison of energy saving of eco-blocks with natural blocks

Name of block	Processes	Scenario 1 (%)	Scenario 2 (%)	Base scenario (%)	Variation (%)
1G eco-blocks	MP 1	25.67	27.37	26.77	0.60-1.10
	MP 2	29.24	30.97	30.77	0.20-1.53
2G eco-blocks	MP 1	30.17	32.27	31.52	0.75-1.35
	MP 2	35.10	37.50	36.94	0.56-1.84
3G eco-blocks	MP 1	25.18	26.73	26.26	0.47-1.08
	MP 2	30.13	32.16	31.72	0.44-1.59

Apart from the input data for cement, other important environmental impacts contributors are the aggregates, the manufacturing process, the TiO_2 and the transport of the manufactured blocks to the user sites (Table 4-5). The study assumed that, the uncertainty related to aggregates, TiO_2, and the manufacturing process should be low due to the use of first-hand data and the use of Europe database for TiO_2 (as imported from Europe). However, the uncertainty or the variation of the environmental impacts due to the transport of the manufactured blocks to the user sites needs to be evaluated. Therefore, sensitivity analysis was also carried out. In this sensitivity analysis, a scenario of transport distance variation (± 20%) was considered and then compared with the base case. Based on the collected data from block manufacturer, the average transport distance is considered as base case (that represents the real case in Hong Kong). However, 20% varying transport distance are considered in this analysis, as it is expected that the transport distance will not be exceed the upper limits. Even with higher transport distance (within Hong Kong), it is expected that the result will not be varied significantly, as the contribution of this distance is quite low compared to the total emission.

The findings are presented in Table 4-8 (for the manufacturing process 1). The results indicate that the variations for both the considered impact categories were negligible (less than 2%). Therefore, it can be considered that the final results were not affected even the transport distance vary by ±20%. The study assumed that the transport distance would not change by more than 20%, as Hong Kong is a small city.

Table 4-8 - Sensitivity analysis by varying distances for paving blocks to user sites

Impact indicator	Transport distance	Natural blocks	1G eco-blocks	2G eco-blocks	3G eco-blocks
Global warming potential (kg CO_2 eq)	Base case	261.45	217.01	209.56	217.34
	+20	263.40	218.96	211.51	219.29
	-20	259.50	215.06	207.61	215.39
	Variation (%)	*0.75*	*0.90*	*0.93*	*0.90*
Non-renewable energy consumption (MJ primary)	Base case	2068.46	1514.76	1416.39	1525.34
	+20	2099.31	1545.61	1447.24	1556.19
	-20	2037.61	1483.91	1385.54	1494.49
	Variation (%)	*1.50*	*2.00*	*2.18*	*2.00*

4.4.5 Allocation of fly ash as by-product

Recycling of waste materials avoids waste landfilling and associated impacts, and also saves non-renewable resources. However, some of the waste materials can be seen as a shift in their status from waste to by-product, including fly ash and blast furnace slag (Chen et al., 2010; Van den Heede and de Belie, 2012). Because fly ash and blast furnace slag meet the conditions as by-products provided by the European Union directive (EU, 2008), fly ash is considered as a by-product in this study, and the consequences of the allocated impact of coal-fired electricity production needs to be assigned to fly ash. Chen et al. (2010) proposed two allocation principles for fly ash, including allocation by mass and economic allocation. The study also calculated that about 12.4% of the total impacts associated with electricity generation from coal-fired plant needs to be assigned to fly ash when mass allocation is considered, whereas it was about 1% when economic allocation was considered. Based on the mass allocation, extremely high environmental impacts are associated with fly ash. For example, CO_2 eq emission, SO_x eq emission and total energy use are about 2.4 kg/kg, 16.7 g/kg, and 29.9 MJ/kg, respectively for fly ash, whereas they were about ±0.8 kg/kg, ±0.5 g/kg and ±2.9 MJ.kg, respectively for cement. This is mainly due to the little fly ash (about 52 g) is produced for per kWh electricity from coal. Hence, the impacts of 19.2 kWh electricity need to be applied to obtain the impacts of 1 kg fly ash (Van den Heede and De Belie, 2012).

In this study, the materials used in the block production were proportioned based on mass. Therefore, the study also assessed the impacts based on the mass allocation for fly ash proposed by Chen et al. (2010). When the allocation rule is followed (by mass) for fly ash as a by-product, the total impacts of several categories are significantly higher for eco-blocks, compared to those of the natural blocks (Table 9). For example, about 58-59% higher impact on the category of respiratory inorganics, 29-31% higher impact on global warming potential, and 36-38% higher impact on non-renewable energy consumption were observed for the eco-blocks (depending on the types of eco-blocks), compared to the natural blocks. However, the impact on acidification potential is almost similar for all the studied blocks, whereas the impacts on ozone layer depletion and aquatic eutrophication were found to be much lower in the eco-blocks than in the natural blocks. In summary, even when the mass allocation for fly ash is considered, the eco-blocks are still sustainable in terms of several emissions, resources saving and waste reduction.

Table 4-9 - Summary of the mid-point results due to the allocation of fly ash as by-product

Impact category	Unit	Natural blocks	1G eco-blocks	2G eco-blocks	3G eco-blocks
Respiratory inorganics	kg PM2.5 eq	0.20	0.49	0.48	0.49
Ozone layer depletion	kg CFC-11 eq	1.21E-06	9.25E-07	-1.95E-06	-1.03E-06
Acidification	kg SO_2 eq	4.74	4.78	4.48	4.84
Aquatic eutrophication	kg PO_4 P-lim	0.002	-0.058	-0.108	-0.106
Global warming	kg CO_2 eq	261	377	370	378
Non-renewable energy	MJ primary	2068	3317	3217	3327

4.5 Summary

Environmental implications of recycled products are often a subject of debate. Therefore, life cycle assessment (LCA) allows an in-depth understanding of the eco-profile of recycled products. In addition, LCA findings provide the scientific background for supporting environmental claims. Eco-blocks have been produced by using locally generated waste materials in Hong Kong. Hence, the present study was conducted to assess and compare the environmental impacts of producing natural paving blocks and eco-blocks using the LCA techniques. Based on the LCA results, the following conclusions can be drawn;

(1) About 27-31%, 32-37%, and 26-32% lower energy is required to produce 1G, 2G, and 3G eco-blocks, respectively, in comparison with the natural blocks. Similarly, about 17-19%, 20-23%, and 17-20% lower GHGs emitted for producing 1G, 2G, and 3G eco-blocks, respectively, than producing the NB.

(2) According to the IMPACT 2002+ method, the selected seven mid-point impact indicators showed the potential benefits and higher savings for producing eco-blocks compared to the natural blocks production.

(3) The 2G eco-blocks have the lowest environmental impacts for all impacts categories with respect to both of the manufacturing processes.

(4) The 3G eco-blocks consumed higher energy and produced higher emission than the 2G eco-blocks due to the use of TiO_2. However, the benefits of using TiO_2 (as it is able to degrade a significant amount of NO_x from the air) were not taken into account in this study, because the study did not consider the use phase of paving eco-blocks.

(5) Among the selected impact categories, the proposed MP 2 showed a lower impact than the MP 1. For example, about 5-7% higher energy can be saved for the eco-blocks than the process 1.

(6) Sensitivity analysis indicated that initial data were very sensitive to the assessed impact categories and verified the reliability of the final results.

Moreover, most of the aggregates used to produce eco-blocks in Hong Kong are locally generated C&D waste and waste glass. Hence, it could save the landfill space, associated impacts, and costs which are very important for a densely populated city like Hong Kong. Based on the environmental performance (findings of the study), natural resource saving, maximizing waste utilization, minimizing waste dumping, and associated resource saving, eco-blocks can be considered as green or eco-product. This is the first ever LCA study on the environmental performance evaluation of both natural concrete paving blocks and paving eco-blocks, which is likely to extend the potential application of eco-blocks to other countries for saving environmental impacts and resources. Therefore, the study recommends the maximum production and application of eco-blocks instead of natural blocks. Hence, it is necessary to strengthen the policy and the market for recycled products to encourage a resourceful treatment of wastes, as well as sustainable constructions.

CHAPTER 5

SUSTAINABLE MANAGEMENT AND UTILISATION OF CONCRETE SLURRY WASTES

5.1 Introduction

Nowadays, environmental protection and sustainability are becoming important issues globally. In most countries, the construction industry is a major source of environmental problems and contributes significantly to natural resource depletion. The construction industry uses approximately 50% of the earth's natural resources and produces 50% of its waste (De Schepper et al. 2014). With the booming of construction activities, a considerable amount of construction and demolition (C&D) waste is generated every day. The conventional waste management method of C&D waste may result in significant environmental impact. According to the Hong Kong Environment Protection Department (HKEPD), over 62,000 tpd (tonnes per day) of C&D waste were generated in 2013, of which 95% were disposed as public filling materials for land reclamation and 5% were disposed of at landfills (HKEPD 2015). The C&D waste management in Hong Kong is now becoming a serious public concern due to the running out of disposal outlets to accommodate the huge amount of solid wastes.

Among the C&D wastes, concrete slurry waste (CSW) generated from the production of concrete is currently disposed of at landfills in Hong Kong. CSW is sourced from the aggregate reclaiming system of ready-mixed concrete batching plants, where over-ordered/un-required fresh concrete is washed out to retrieve the aggregates and concrete mixer trucks are cleaned. The wastewater is then treated in a sedimentation tank, where the suspended solid particles in the wastewater are deposited and dewatered to form the CSW. A schematic diagram and a picture of CSW generation processes in a concrete batching plant in Hong Kong are shown in Figure 5-1.

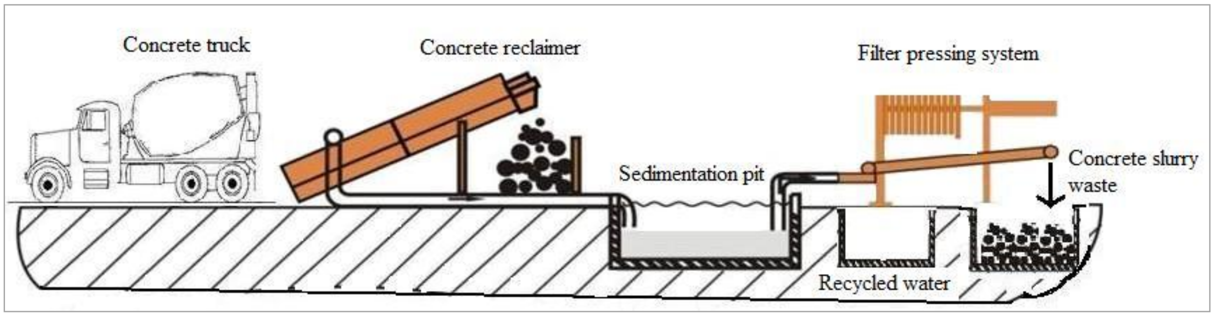


Figure 5-1 - Schematic diagram of CSW generation process in concrete batching plant

In the literature, a few recycling and reuse strategies of CSW have been reported and they include replacement of natural aggregates in concrete or concrete products (Kou et al. 2012a,b), using it as a cementitious material in road bases (Zhang and Fujiwara 2007), a filler in concrete (Correia et al. 2009; Zervaki et al. 2013), a glass-ceramics component (Tian et al. 2007), and a slurry-based geo-polymer (Yang et al. 2009), although the most common destination is landfilling (Tam 2008; Sealey et al. 2001). Schoon (2014) and Schoon et al (2015) investigated the possible use of sludge from concrete plants in the cement production, and concluded that it cannot be classified as a feasible alternative raw material for Portland clinker production. In addition, the concrete slurry wash water can also be reused in new concrete (Chatveera et al. 2006; Su et al. 2002), and as a sorbent of chemicals, such as CO_2 capture, phosphorus recovery and water clarification (Iizuka et al. 2012a,b). The authors' research team has developed a new approach to recycle and reuse fresh CSW as a cementitious paste to produce a type of partition wall blocks, namely 'eco-partition wall blocks', which is produced by proportioning appropriate amounts of fine recycled concrete aggregates (FRCAs) (<5.0 mm) and fresh CSW and subject the mixture to an accelerated mineral carbonation process.

Life cycle assessment (LCA) is considered as an effective tool for evaluating the environmental impacts associated with a process or a product through identifying, quantifying and assessing the impacts, and it is widely applied in eco-labeling programs, strategic planning, promotion, process improvement and product design globally (Reza et al. 2011). A number of LCA studies have been focused on quantifying the environmental impact of conventional construction products and materials (Omar et al. 2014; Broun and Menzies 2011; Sanchez et al. 2009; Broun et al. 2014; Liu et al. 2014; Hong et al. 2012; Bovea and Powell 2016; Ding et al. 2016). But no LCA study had been conducted to assess the environmental sustainability of various CSW management strategies, and construction products produced with CSW. Therefore, this study was conducted to assess and compare the environmental sustainability of different CSW management strategies and their utilisation for the production of partition wall blocks by the LCA technique. The present study would help to promote sustainable CSW management strategy.

5.2 Materials and methods

5.2.1 Current CSW management strategies

So far, the management of CSW generated from concrete batching plants in Hong Kong is mainly by disposal at landfills. Before transporting to landfill sites, CSW containing residual cement powder and fine particles is processed by a dewatering system. The fresh CSW with rich water content is still workable for a few days. When CSW becomes hardened in a few months, it can be further crushed to produce recycled aggregates and supplementary cementitious materials. The four current and proposed strategies for CSW management as shown in Figure 5-2 are described below:

- ***Strategy 1:*** Landfilling: including transport and normal procedures for C&D waste landfilling
- ***Strategy 2:*** Producing supplementary cementitious material (SCM): including grinding and sieving processes
- ***Strategy 3:*** Producing recycled fine/coarse aggregates: including collection and transport of hardened CSW, and then crushing and sieving processes
- ***Strategy 4:*** Using fresh CSW as a cementitious paste: including collection and transport of fresh CSW and directly reusing (within 3 days) in construction products (e.g. partition wall blocks).

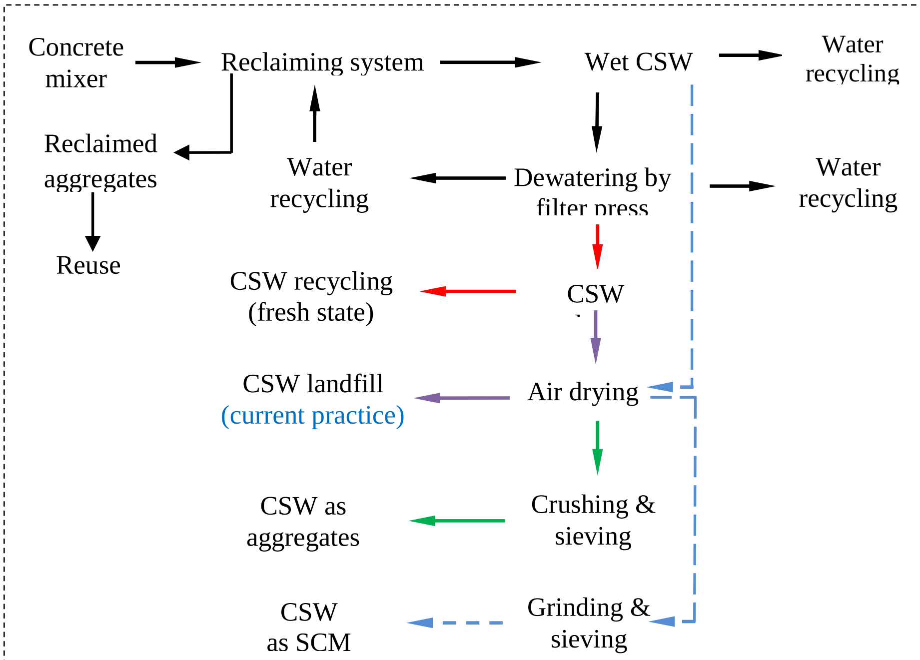


Figure 5-2 - Different strategies of CSW management

5.2.2 Description of different CSW management strategies

The different possible outlets of CSW are shown in Figure 5-3. The most common practice for CSW management is landfill disposal (strategy 1) (Kou et al. 2012b). For landfill disposal, the dewatered fresh CSW is transported from the concrete batching plants to the landfill sites. However, this approach is not an environmentally sustainable option due to the energy consumption and emissions associated with transport and handling. Moreover, due to the high alkaline content in CSW, the indiscriminate disposal of CSW at landfills may cause detrimental effects to the surrounding environment and ecosystems (Sealey et al. 2001).

Alternative management options such as (i) reuse as a supplementary cementitious material (SCM) (strategy 2), (ii) use as recycled aggregates as the substitution of natural aggregates (strategy 3), and (iii) reuse fresh CSW as a cementitious paste in construction products (strategy 4) have been proposed by several studies. It is noticed that several pre-processing steps (e.g. crushing and sieving) are required to prepare CSW as aggregates or SCM.

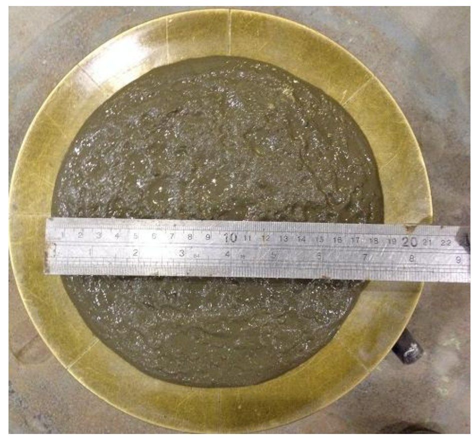
Some technical breakthroughs are required to use CSW in new construction products. For example, recycled aggregates produced by hardened CSW can be used as an alternative aggregate in concrete to replace natural aggregates. However, the use of 100% recycled CSW aggregates is likely to have a negative influence on concrete properties, e.g. compressive strength, modulus of elasticity, shrinkage and creep (CCANZ Technical report 2011). Kou et al. (2012b) showed that about 50% recycled fine CSW aggregates may be used to substitute river sand for producing non-load bearing concrete products like partition wall blocks. Correia et al. (2009) concluded that although the use of recycled fine CSW aggregates as a substitute of river sand decreased the workability of the fresh concrete, good 28-day compressive strength (32–44 MPa) may still be achieved even with high water-cement ratios (0.40-0.60) when the replacement level was at <30%. In addition, using dried CSW powder as SCM has been considered as a type of soil stabiliser. However, little information has been reported on using dried CSW powder as a SCM in other construction products like concrete blocks and concrete.

In order to identify a resource-efficient solution for utilizing CSW in construction products, the present study was conducted to assess and compare the environmental sustainability of partition wall blocks prepared with different scenarios (described elaborately in Section 5.2.3) using FRCA as recycled aggregates and fresh CSW slurry as a cementitious paste.

(a) Dewatered fresh concrete waste

(b) Recycled aggregates from CSW

(c) SCM from CSW



(d) Fresh CSW cementitious paste

Figure 5-3 - Different outlets of concrete slurry waste

5.2.3 Life cycle assessment of partition wall blocks

The following four scenarios for producing partition wall blocks are compared using the standard life cycle assessment tools recommended by the ISO 14040-14044 (ISO 2006a,b):

- ***Scenario 1:*** Partition wall blocks prepared with natural aggregates (crushed stone) and ordinary Portland cement (OPC)
- ***Scenario 2:*** Eco-partition wall blocks prepared with FRCAs, crushed stone (as aggregates) and OPC
- ***Scenario 3:*** Eco-partition wall blocks prepared with recycled aggregates produced from CSW, natural aggregates (crushed stone and river sand) and OPC
- ***Scenario 4:*** Eco-partition wall blocks prepared with FRCAs (as aggregates), fresh CSW (as a part of binder), and OPC.

5.2.3.1 Mix design of partition wall blocks

The elemental compositions of OPC, FRCAs and CSW are listed in Table 5-1 (determined by using X-ray fluorescence spectroscopy). The mix designs of the partition wall blocks are given in Table 5-2. All types of partition wall blocks met the minimum compressive strength requirement according to the BS 6073-1 (>7.0 MPa) (BS 6073-1 2008).

Table 5-1 - Elemental compositions of CSW, FRCAs and OPC

Oxide (%)	OPC	CSW	FRCAs
MgO	1.48	1.88	0.59
Al_2O_3	3.81	8.21	9.64
SiO_2	19.57	32.84	57.37
SO_3	5.43	2.81	1.53
K_2O	0.69	1.60	3.41
CaO	64.51	36.92	17.90
TiO_2	0.27	0.54	0.29
Fe_2O_3	3.12	6.72	3.27
LOI	1.08	8.58	5.61

Note: LOI: the loss on ignition after 1050℃.

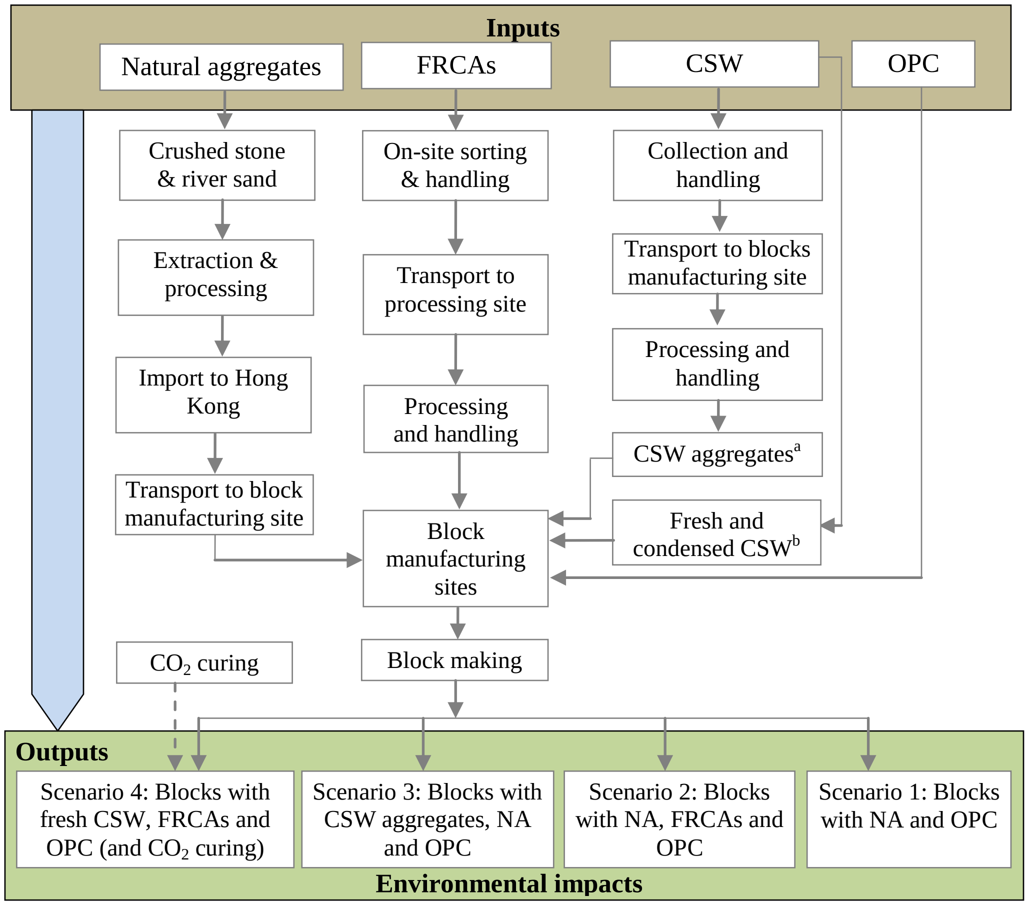
Table 5-2 - Mix-designs of partition wall blocks produced by different scenarios (per kg of blocks produced)

Materials	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CSW (kg)				0.320
FRCAs (kg)		0.455		0.655
OPC (kg)	0.091	0.090	0.08	0.025
River sand (kg)			0.30	
CSW aggregates (kg)			0.30	
Natural aggregates (crushed stone) (kg)	0.909	0.455	0.32	
*Compressive strength (MPa)	19 [a]	20 [b]	25 [a]	18 [b]

* after 28 days of curing; [a,] Kou et al. 2012b; [b,] Xuan et al. 2015

5.2.3.2 Goal, functional unit and system boundary

The objective of this study was to assess and compare the environmental sustainability of partition wall blocks prepared with CSW and traditional concrete partition blocks by LCA. The system boundary for the LCA was 'cradle-to-gate', which included raw material extraction/collection, processing, transport to the blocks manufacturing site, and blocks production (Figure 5-4). The assessment was based on the environmental impact for producing 1 kg of partition blocks. As the system boundary was cradle-to-gate, the assessment did not include the transport from the blocks factory to users' sites, and the maintenance and end-of-life disposal was also excluded from the impact assessment.



NA, natural aggregates; FRCAs, fine recycled concrete aggregates; CSW, concrete slurry waste; [a], Strategy 3; [b], Strategy 4

Figure 5-4 - Process map of partition wall blocks production with the cradle-to-gate system boundary

5.2.3.3 Data collection and impact assessment

The required first hand data for conducting this LCA were collected from the C&D waste recycler in Hong Kong, and the natural aggregate manufacturer and supplier at Guangdong province in China. The functional unit data was calculated based on the total production, and the total energy (e.g. electricity) and fuel (e.g. diesel) consumptions (Table 5-3 and Table 5-4). The average distances of C&D waste collection to the processing sites, and then to the blocks manufacturing sites were actual local data. This study identified eight concrete batching plants in

Hong Kong for collecting CSW, and then the average distances to the block manufacturing site and also to the landfill sites (for avoided impact) were calculated. The transport distances for other materials, including cement and natural aggregates are listed in Table 5-3. For the upstream data (for example, electricity generation, fuel consumption, and transportation), the Chinese Life Cycle Database (CLCD) and the China Light and Power (CLP) were used. The CLCD is a national LCI database for key materials and chemicals, energy and energy carriers, transport, and waste management in the Chinese market. Because Hong Kong is a Special Administrative Region (SAR) of China, the use of the CLCD database rather than other databases would be more appropriate (Hossain et al. 2016b,c). As some of the materials and processes were not available in the CLCD database, the European reference Life Cycle Database (ELCD) and literature were used. For example, the environmental impact of landfilling of inert wastes was assessed based on the ELCD database 3.0 (Table 5-4). Finally, LCI data of the downstream processes, (e.g. material collection, blocks manufacturing, etc.), were collected from an eco-block producer in Hong Kong as first hand data.

A midpoint approach was selected to assess the environmental impact of the production of the partition wall blocks. Based on their importance and priority, six mid-point impact indicators (e.g. Global warming potential as CO_2 eq, non-renewable energy consumption as MJ, respiratory inorganics as PM2.5, acidification potential as SO_2 eq, aquatic eutrophication as PO_4 P-lim eq, ozone layer depletion as CFC-11 eq) were selected and then assessed by the IMPACT 2002+ Method (Jolliet et al. 2003).

Table 5-3 - Materials and transport distances for the production of eco-partition wall blocks

Materials	Transport location	Transport type and distance
Cement	Local cement plant to block manufacturing site	5 km by 30 t trucks
CSW	Concrete batching plant to block manufacturing site*	30 km by 30 t trucks
CSW (landfill)	Variable*	35 km by 30 t trucks
C&D waste (recycled)	Variable*	45 km by 30 t trucks
C&D waste (landfill)	Variable*	35 km by 30 t trucks
Natural aggregates (crushed stone)	Guangdong Province, China	128 km by inland barge; 50 km by 30 t trucks
Natural aggregates (river sand)	Guangdong Province, China	128 km by inland barge; 20 km by 30 t trucks

* The distance is variable due to different geographic locations (the average distance is used)

Table 5-4 - Energy requirements for materials/processes and database used

Materials/processes	Energy requirement	Upstream data source
Natural fine aggregate (crushed stone)	R^a	CLP 2014; CLCD 2010c,d
Natural fine aggregate (river sand)	R^a	CLP 2014; CLCD 2010c,d
Recycled fine concrete aggregate (from C&D waste)	R^a	CLP 2014; CLCD 2010c,d
Landfill of waste materials (C&D waste and CSW)	R^b	ELCD 2013
Cement production	R^b	CLCD 2010b
Blocks making process including running pump for water	109 MJ/t blocks (electricity)	CLP 2014; CLCD 2010c
On-site handling	8 MJ/t blocks (diesel)	CLCD 2010d
Transport, road	R^b	CLCD 2010e
Transport, sea (Inland barge)	R^b	CLCD 2010a

R^a, Hossain et al. 2016b,c; R^b, Referring to the databases mentioned in this Table

5.2.4 Accelerated mineral carbonation of partition wall blocks

An accelerated mineral carbonation technology was employed to cure the partition wall blocks prepared with CSW and FRCAs using a waste CO_2 source for 24 hour (in the experiment, a pure 100% CO_2 source was used for simplicity) (Xuan et al. 2015). This process not only accelerated the curing and strengthening process of the blocks but also sequestrated CO_2 due to the carbonation reactions of CSW and FRCAs. The mechanical properties of the blocks after the CO_2 curing were comparable to the 28-day air-cured blocks (Xuan et al. 2016; Owsiak et al. 2015; Chang et al. 2014). The amount of CO_2 uptake by the blocks was determined basing on the decomposition of calcium carbonates between 550-850℃ (Xuan et al. 2015). The net carbon emission (CO_{2N}) was calculated by considering the total measured emissions through the 'cradle-to-gate' LCA system boundary ($CO_{2\ LCA}$) and the total uptake during the CO_2 curing phase as carbon credit ($CO_{2\ Credit}$). The calculation of net carbon emission by the carbonated blocks can be expressed by Equation 5-1;

$$CO_{2_N} = CO_{2_{LCA}} - CO_{2_{credit}} \quad (5\text{-}1)$$

5.3 Results and discussion

5.3.1 Environmental impacts of partition wall blocks

The environmental impacts of the production of partition wall blocks using different scenarios were assessed. During the assessments, the avoided impacts were included due to avoiding disposal of the corresponding amount of waste materials at landfills. A summary of the environmental impacts for producing 1 kg of partition wall blocks by adopting different scenarios are given in Table 5-5. For the blocks produced with CSW and FRCAs (scenario 4), it had the lowest impact in all impact indicators. The low impact was due to the reuse of FRCAs (scenario 2), CSW aggregates (scenario 3), and most significantly due to the use of fresh CSW and FRCAs together (scenario 4). The use of FRCAs reduced the transport impact of natural aggregates, and using CSW reduced the production and transport impacts of cement.

Table 5-5 - Environmental impacts of partition wall blocks production by different scenarios

Impact indicators	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Global warming potential (kg CO_2 eq)	0.144	0.133	0.114	0.046
Non-renewable energy consumption (MJ eq)	1.354	1.200	1.044	0.532
Acidification potential (g SO_2 eq)	3.068	2.741	2.151	1.243
Respiratory inorganics (g PM2.5 eq)	0.132	0.120	0.102	0.062
Aquatic eutrophication (g PO_4 P-lim)	0.636	0.464	0.324	0.124
Ozone layer depletion (mg CFC-11 eq)	9.61×10^{-4}	7.22×10^{-4}	5.30×10^{-4}	2.01×10^{-4}

A comparative analysis of environmental impacts is further illustrated in Figure 5-5. Comparisons are made between the four production scenarios of partition wall blocks stated in the study. Based on the LCA results (summarized in Table 5-5), it can be noticed that approximately 61%, 56% and 49% lower non-renewable energy use was associated with scenario 4 when compared with scenario 1, scenario 2 and scenario 3, respectively. The LCA results also show about 0.144, 0.133, 0.114 and 0.046 kg CO_2 eq GHGs were emitted for producing 1 kg normal partition wall blocks (scenario 1), eco-partition wall blocks with FRCAs (scenario 2), eco-partition wall blocks with CSW aggregates (scenario 3), and eco-partition wall blocks with fresh CSW and FRCAs (scenario 4), respectively (Table 5-5). Compared to the normal partition wall blocks (scenario 1), about 8% and 21% lower GHGs emission was associated with scenario 2 and scenario 3, respectively, because of a relatively long transport distance of the natural aggregates. Similarly, 68% lower GHGs emission was associated with the production and transport of the eco-partition wall blocks prepared with CSW and FRCAs (scenario 4), compared to scenario 1. This is due not only to the use of FRCAs as a substitution of natural aggregates, but also because of the reuse of fresh CSW to replace cement compared to the other types of partition wall blocks.

Similarly, about 25%, 45% and 79% lower impact on the category of ozone layer depletion was associated with eco-partition wall blocks production for scenario 2, scenario 3 and scenario 4, respectively compared to scenario 1. For acidification potential, approximately 11% and 30% lower impact was observed for eco-partition wall blocks for scenario 2 and scenario 3, respectively, compared to the normal blocks (scenario 1). However, the corresponding acidification reduction was about 59% for scenario 4 (eco-partition wall blocks with CSW and FRCAs), compared to normal blocks (scenario 1). The emission of PM2.5 eq for the effects of respiratory damage, about 9%, 23% and 53% lower impact were associated with scenario 2, scenario 3 and scenario 4, respectively, when compared to scenario 1.

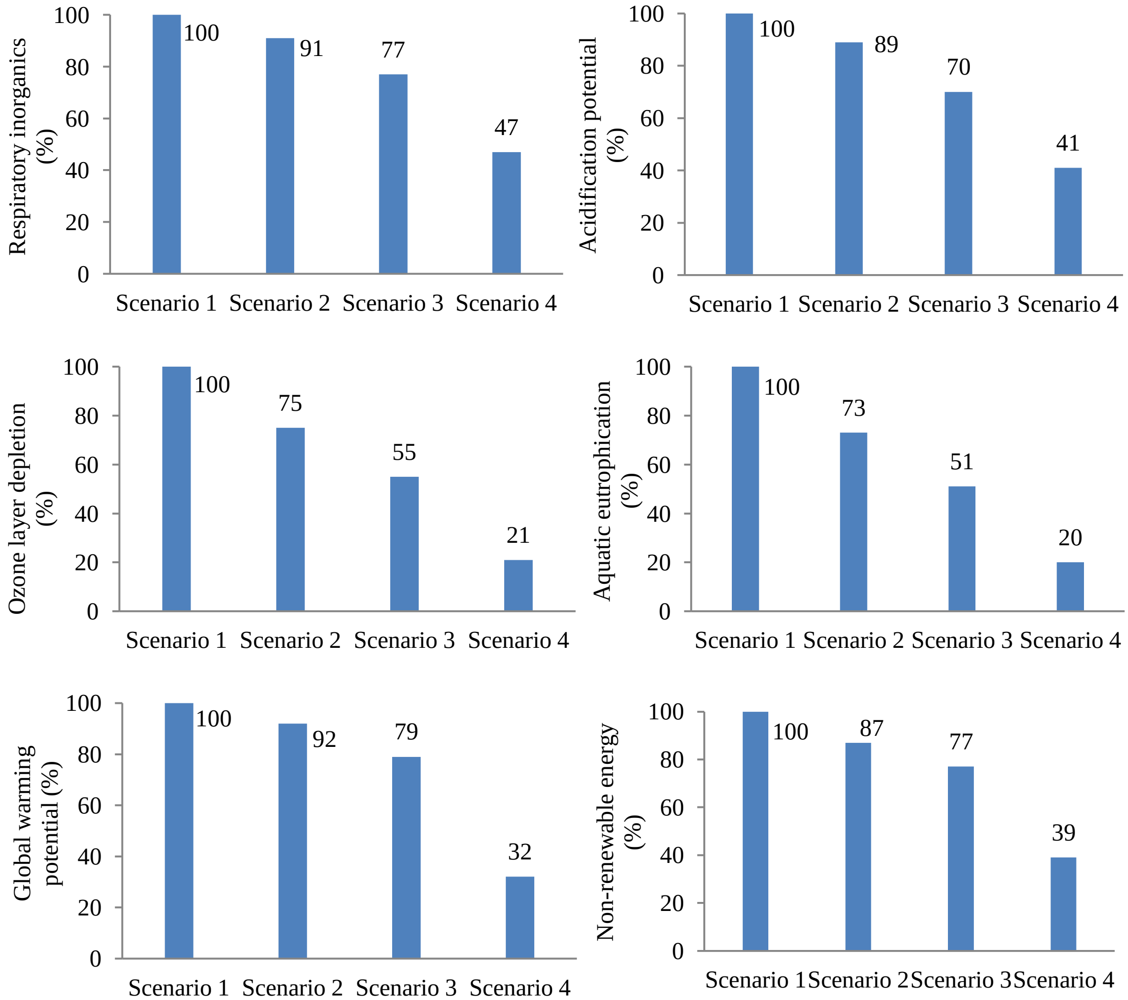


Figure 5-5 - Comparative impacts of different production scenarios

5.3.2 Contribution analysis to the impact indicators

The contribution of different materials and processes to non-renewable energy consumption and greenhouse gas emissions for the production of partition wall blocks is shown in Table 5-6. For normal partition wall blocks production (scenario 1), use of cement accounted for the highest energy consumption (about 37%), where 35% of the energy use was for natural aggregate production and transport, and 28% was for blocks manufacturing. For producing eco-partition wall blocks (scenario 2), cement also contributed higher impact to the energy consumption (42%), while 20%, 7% and 31% were respectively for NA, FRCAs and blocks making. For eco-partition blocks production with CSW aggregates and natural materials (scenario 3), about 42%, 10%, 16%, -4% (savings of reusing CSW aggregates and avoid impact) and 36% of the total energy are accounted by the use of cement, river sand, crushed stone, CSW aggregates and blocks making, respectively. In addition, about 26%, -19% (savings of reusing fresh CSW and avoid impact), 22% and 71% energy was attributed to cement, CSW, FRCAs and blocks manufacturing, respectively, for the production of eco-partition wall blocks (scenario 4). The contribution of different materials and processes to the greenhouse gases emission for producing different types of partition blocks had a similar trend (Table 5-6).

Table 5-6 - Contribution analysis (%) of partition blocks production for different scenarios

Component	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	NRE	*GWP*	*NRE*	*GWP*	*NRE*	*GWP*	*NRE*	*GWP*
Cement	37.30	65.37	42.06	70.41	42.48	70.36	26.13	56.54
NA (river sand)					9.82	6.00		
NA (crushed stone)	34.78	20.77	19.61	11.19	15.92	9.18		
FRCAs			6.85	3.48			22.37	15.25
CSW aggregates					-4.52	-2.94		
Fresh CSW							-19.55	-15.21
Blocks making	27.92	13.86	31.48	14.92	36.30	17.40	71.05	43.42
Total (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

GWP, Global warming potential; NRE, Non-renewable energy; all values in percentage

5.3.3 Mineral carbonation of partition wall blocks with CSW and FRCAs

The total CO_2 uptake through accelerated mineral carbonation of the partition wall blocks produced with CSW and FRCAs was determined and given as 'Carbon Credit'. Adopting accelerated mineral carbonation for the production of concrete blocks and products was to obtain the required strength quickly, and capture and store CO_2 in the blocks (Thiery et al. 2013; Zhan et al. 2013; El-Hassan and Shao 2014; Siriruang et al. 2016). For the carbonation processing, CO_2 may be collected from emissions of industrial combustion processes or landfill gas. According to the carbon dioxide uptake results in this study, it is estimated that about 0.052 kg CO_2 can be sequestrated per kg of partition blocks produced (scenario 4). By applying Equation 5-1, the net life cycle carbon emission was calculated for producing the partition wall blocks (producing and transporting raw materials and blocks manufacturing, and the carbon uptake through carbonation (Table 5-7). The results show that approximately 104% lower carbon emission was observed for the carbonated partition wall blocks produced with CSW and FRCAs when CO_2 uptake was accounted for, when compared to the normal partition wall blocks (scenario 1). Based on the LCA results, carbonated partition wall blocks can be considered as environmentally sustainable products, due to its carbon neutral (even negative) characteristics. It can also be noticed that the total energy consumptions for the production the partition wall blocks (scenario 4) with and without mineral carbonation were similar, as very little additional energy (about 1%) was required for the carbonation process.

Table 5-7 - Total CO_2 emission for partition wall blocks production of scenario 4

Partition wall blocks	Considerations	$CO_{2\ LCA}$ (kg/kg block)	$CO_{2\ Credit}$ (kg/kg block)	$CO_{2\ N}$ (kg/kg block)	Compared with normal blocks (%)
Eco-partition wall blocks (scenario 4)	Without mineral carbonation	0.046	--	0.046	<68
	With mineral carbonation	0.046	0.052	-0.006	<104

5.4 Summary

The use of recycled materials in the construction sector promotes a more sustainable society, and also creates a new market opportunity for construction products. Producing partition wall blocks with fresh CSW and FRCAs can save natural aggregates, cement, and landfill space and mitigate their associated impacts, which are very important for a compact and resource scare city, like Hong Kong. The present study was conducted to assess and compare the environmental sustainability of CSW management strategies and utilisation in producing eco-products by LCA. Based on the findings of the study, the following conclusions can be drawn:

(i) Compared to normal partition wall blocks (scenario 1), high impact saving was found for all impact categories (8-27% for various indicators) for partition wall blocks prepared with recycled fine concrete aggregates (scenario 2).

(ii) The reuse of fresh CSW in the eco-partition wall blocks showed the lowest environmental impacts among all the assessed production scenarios. Compared to normal partition wall blocks (scenario 1), about 68% impact on GWP, 61% on non-renewable energy, 59% on acidification, 53% on respiratory damage, 79% on ozone layer depletion and 80% on aquatic eutrophication can be saved by producing the partition wall blocks by using fresh CSW and FRCAs (scenario 4).

(iii) Reuse and utilization of fresh CSW in producing eco-partition wall block was the preferable strategy than the others based on environmental performance.

(iv) Using CO_2 curing to produce carbonated partition wall blocks with CSW and FRCAs (scenario 4) is able to further lower the carbon emissions and the blocks produced may even be considered as carbon neutral.

CHAPTER 6

SUSTAINABLE STRATEGIES FOR REDUCTION OF ENVIRONEMTAL IMPACTS IN THE CEMENT INDUSTRY

6.1 Introduction

The construction industry uses huge amounts of raw materials and requires high energy consumption and thus is viewed as an industry causing natural resources depletion and negative environmental impacts (Bribian et al. 2011). The environmental impact of the production of cement, one of the most commonly used construction material, is of great concern, especially associated with its high greenhouse gases (GHGs) emissions and high energy consumption (Mikulcic et al. 2016). Its world production contributes to 5-10% of the total anthropogenic CO_2 emissions (Scrivener and Kirkpatrick 2008), and 12-15% of total industrial energy use (Madlool et al. 2011). In cement manufacturing, about half of the CO_2 emissions are sourced from the combustion of fossil fuels, and the remaining half is emitted from the calcination of limestone (Gursel et al. 2014). Furthermore, the total energy requirement for cement production strongly depends on the geographical location, technology, production efficiency, energy mix used for electricity generation, and the selection of kiln fuels (Gursel et al. 2014).

To face this global sustainability concern, cement manufacturers are keen in lowering the emissions and energy consumption. Generally, to achieve sustainability in product manufacturing requires redesigning/modifying the production processes, efficient consumption of resources and waste management (Cucek et al. 2012). The use of less primary materials and more renewable resources (e.g. renewable energy), and the reduction of emissions from the production process are required to achieve sustainability in cement manufacturing (Li et al. 2014).

Several studies were reported on the sustainability of cement production, such as works to develop potential technological improvements for cement manufacturing in France (Habert et al. 2010), promoting cleaner production in Italy (Strazza et al. 2011), assessment of cement plant variability and process scenarios in France (Chen et al. 2010a), potential improvements in energy efficiency and emissions in EU (Moya et al. 2011; Josa et al. 2007), design for economical cement manufacturing in Malaysia (Benhelal et al. 2013), promoting alternative technologies for OPC manufacturing in US (Huntzinger and Eatmon 2009), improvements of CO_2 performance in Switzerland (Feiz et al. 2014), and technological improvements for OPC production in China (Li et al. 2014). In addition, Garcia-Gusano et al. (2015) proposed CO_2 capture technology using monoethanolamine as absorbent to mitigate global warming in Spanish cement production. In addition, several attempts have been done on the use of by-products as alternative raw materials for Portland cement clinker in Belgium. For example, the possible use of sludge from concrete plants, and concluded that it cannot be classified as a feasible alternative raw material for Portland clinker production (Schoon 2014; Schoon et al. 2015a), but fines fractions generated from concrete recycling plants, fibrecement recycled materials, cellular concrete, and fines and sludge from porphyry or dolomitic limestone aggregates can be potentially used as an alternative raw material for Portland clinker production (Schoon et al. 2015b; Schoon et al. 2012; Schoon et al. 2013a; Schoon et al. 2013b).

In an effort to evaluate the sustainability of cement production, a holistic analytical approach is strongly recommended. Life cycle assessment (LCA) has been extensively used to evaluate the environmental impacts, understand total energy consumption, identify energy-saving and emission reduction opportunities, and inform decision-makers regarding policies and energy-efficient investments (Lu 2010; Valderrama et al. 2012).

In Hong Kong, about 51% (about 1.41×10^6 t/y) of the total supply of cement are locally manufactured and the rest 49% are imported (Zhang et al. 2014). Hong Kong Government has set a target to reduce carbon intensity by 50-60% by 2020 at the level of 2005 (Environmental Bureau 2010). It will be a challenge to achieve this reduction target without the emission reduction from the cement industry, as the industry contributes to a significant amount of GHGs emissions in Hong Kong (Cornish et al. 2011).

The use of alternative fuels has significantly increased recently, but scope for further improvements still exists. As significant amounts of GHGs emissions are resulted from the combustion of fossil fuels, the use of alternative fuels in the cement industry is conducive to reducing GHGs emissions. Various types of alternative fuels have been used globally in the cement industry, such as wastewater treatment plant sludge, waste plastics, scrap tires, automobile shredder residues and wood residues in the US (USEPA 2008), biomass wastes in the Netherlands (ENCI Cement 2007), wood chips, palm shells, palm fibers, saw dusts and barks in Thailand (VCS, 2009), wood and industrial wastes in Japan (SOC 2012), and biomass waste in Costa Rica (CEMEX 2012). In addition, new materials might also play a significant role in the future for the production of sustainable cement (Schneider et al. 2011). Most of the previous LCA studies have focused on the technological improvements and plant variability (e.g. Habert et al. 2010; Chen et al. 2010a; Garcia-Gusano et al. 2015), and the use of fly ash and granulated blast furnace slag in producing blended cement (e.g. Li et al. 2016; Pushkar and Verbitsky 2016; Saade et al. 2015; Huang et al. 2016). Yang et al. (2016) compared the environmental impacts of different types of cement production in China using LCA. Fyffe et al. (2016) presented the potential energy and environmental trade-offs of using alternative fuels derived from municipal solid waste in the cement industry in USA. Gabel and Tillman (2005) discussed the environmental performance of cement manufacturing using different operational alternatives including the use of industrial by-products and wastes as raw materials and fuels in Sweden. Similar studies were conducted by Reza et al. (2013) and Zhang and Mabee (2016) in Canada. Reviews on using waste materials for cleaner cement production have been conducted by Galvez-Martos and Schoenberger (2014), Mikulcic et al. (2016) and Rahman et al. (2015). Moreover, a review of using waste glass and its technical performance in the production of concrete and cement was conducted by Shi and Zheng (2007).

Among the previous LCA studies conducted on cement manufacturing, only a few studies have focused on the comparative impact assessment for various types of cement with the same strength class. A few types of cement, namely, ordinary Portland cement (OPC) and Portland-fly ash cement (PFC) are currently produced in Hong Kong. A case specific LCA study is needed to assess and compare the environmental impact associated with the production of each type of cement. Within the system boundary of 'cradle-to-gate', this study evaluated and compared the environmental impacts of different types of cements manufactured in Hong Kong by considering their strength class. In addition, no LCA study has been found on sustainability assessment of cement production by utilizing bio-energy generated from wood waste to substitute coal, and waste glass cullet to substitute clinker. In order to reduce the environmental impacts of the cement industry in Hong Kong, this study proposed two different strategies for the reduction of environmental impacts in different stages of cement production, which are: (i) the use of glass cullet from locally generated waste glass bottles as a raw material, and (ii) the use of bio-fuels (wood pellets) produced from locally generated wood wastes as a co-fuel with coal.

6.2 Methodology

A case-specific LCA approach was used for a comprehensive and comparative environmental impact assessment of different types of cement production in Hong Kong by following the principle of LCA provided by ISO standards (ISO 14040 2006).

6.2.1 Composition of cements considered in this study

The compositions of the commercially available cement types manufactured in Hong Kong are listed in Table 6-1 (GIC 2014). In addition, the production of an eco-glass cement (Eco-GC-2), a new type of cement, is proposed in this study (details are provided at sections 6.2.2 and 6.2.3).

Table 6-1 - Compositions of different types of cements

Materials	Type of cement			
	Ordinary Portland cement (OPC)	Portland-fly ash cement (PFC)	Eco-glass cement (Eco-GC-1)	Eco-glass cement (Eco-GC-2)
Clinker (limestone 80%, sand 9%, clay 9% and iron ore 2%)	92%	75%	90%	75%
Gypsum	5%	5%	5%	5%
Pulverized fly ash	--	20%	--	--
Limestone powder	3%	--	2%	--
Glass cullet	--	--	3%	20%
Total	100%	100%	100%	100%

According to GIC (2014), the compressive strength of OPC and Eco-GC-1 is similar (Strength class: CEM I 52.5 N; Conforms to BS EN 197-1:2000 specification). In addition, the strengths (e.g. 7 days, 28 days, and 90 days) of PFC and Eco-GC-2 have been assessed with OPC comparably in order to assess the environmental impacts based on the strength class (described at sections 6.3.1.1 and 6.3.1.2).

6.2.2 Strategies for reducing environmental impacts in the cement industry

Several alternative strategies can be adopted in order to promote sustainability in the cement industry, such as the use of alternative fuels and alternative raw materials (Schneider et al. 2011). This study proposed two strategies in order to reduce the environmental impacts from the cement industry in Hong Kong, which included;

- *Use of alternative fuels:* Wood pellet produced from recycled wood waste can be a good potential source of energy which can be used as alternative fuel to substitute fossil fuel.
- *Use of alternative raw materials:* The use of alternative raw material such as glass cullet generated from locally available waste glass in the cement production (Eco-GC-2 cement) can be a good source to reduce environmental impacts and to save natural resources (e.g. clinker).
- *Application of combined strategies:* Adoption of these two strategies in the cement industry to assess the influence of different recycling rate on the potential environmental impacts reduction.

The strategies proposed in this study can be implemented locally (details can be found in sections 6.2.3 and 6.2.5).

6.2.3 Scope, system boundary and functional unit

The 'cradle-to-gate' system boundary was employed in this study, including the extraction of raw materials, transport to the plant, processing/upgrading of materials and cement manufacturing, by using the functional unit of 1 tonne of cement production. The system boundary and framework of manufacturing is shown in Figure 6-1. The principal raw materials are limestone, clay, sandstone, iron ore and gypsum (Zhang 2011).

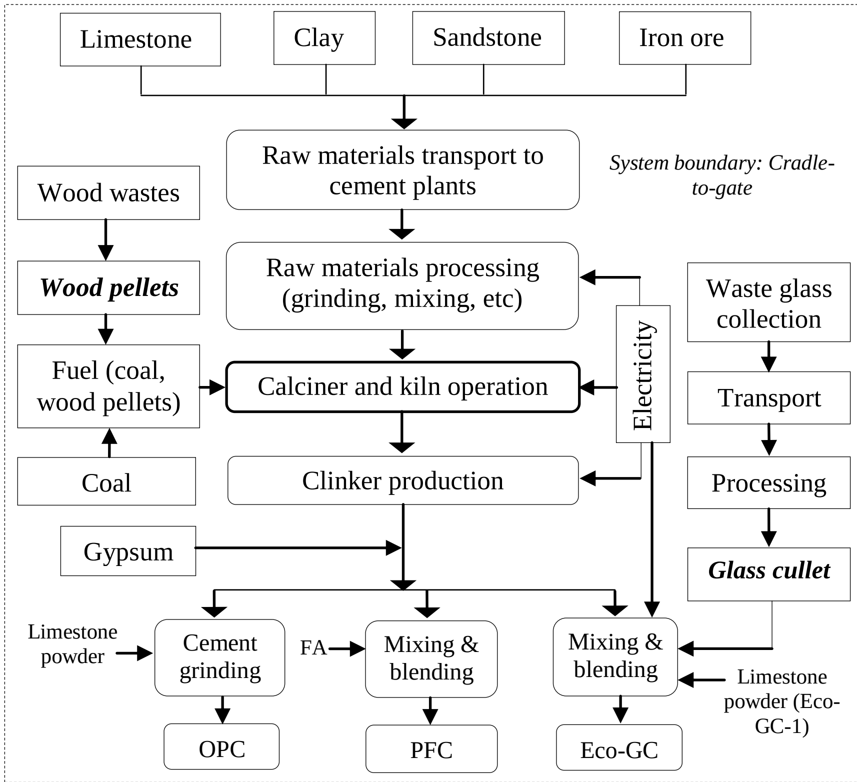
The raw materials for clinker production are imported and transported from various locations (e.g. mainland China, Japan and the Philippines) to the manufacturing plant in Hong Kong and they are then separately grinded to make fine powders. Transport distances for different materials were considered based on the proportions of the materials used. A synthetic gypsum is used in cement manufacturing in Hong Kong which is a by-product of the flue-gas desulfurization process in the local coal-fired power plants.

A certain amount of limestone and synthetic gypsum powder is added to the clinker to produce OPC (see Table 6-1). The mined and processed (including crushing) limestone is imported to Hong Kong from the Philippines. After receiving by the plant, the limestone is then grinded to make the fine powder. The limestone powder is then mixed and blended with the clinker and gypsum to produce the OPC.

In the Portland-fly ash cement, a certain amount of fly ash (20% wt) is used to replace the clinker. Fly ash (FA), is a by-product generated from coal-fired power plants. It is estimated that the transport distance of fly ash from the power plant to the cement manufacturing site is about 6 km based on the actual locations of the two plants. In addition, about 9.3 kWh per tonne of energy consumption is required for the processing of FA to use it as a supplementary cementitious material in cement (MPA 2009). For simplicity, FA is used with the 'no allocation' principle in this study (Chen et al. 2010b; Van den Heede and De Belie 2012), which means no upstream environmental impacts due to coal combustion in the power plant (for energy generation) have been allocated to FA.

Currently, Hong Kong is also manufacturing another type of environmental friendly cement, called 'eco-glass cement (Eco-GC-1)' on a trial basis, which can incorporate a considerable amount of glass cullet obtained from locally generated waste glass bottles. The waste glass cullet is used as a partial replacement of the clinker phase. In fact, the collection and processing of waste glass are energy intensive. There are three possible ways of waste glass collection in Hong Kong, such as glass bottles are recovered from designated recycling bins, hotels and shops, refuse transfer stations and landfill sites. The recycling and collection system of waste glass bottles had been described in our previous papers (Hossain et al. 2016b,c). The average distance of waste glass collection and transport to the cement manufacturing site was estimated. After collection, waste glass goes through several processing steps before use in the blended cement. The first process is by crushing the glass bottles to glass cullet (<3.55 mm). Mechanical forklifts and conveyers are used for on-site handling and transport the cullet to the storage bunker. The cullet can either be used as raw material to produce clinker or grounded with clinker to produce blended cement (Chen et al. 2002). To make blended cement with glass, the clinker dosed with controlled amounts of gypsum and cullet (<4 mm) are fed into a finish mill (Sobolev 2003). The finish mill is a horizontal steel tube filled with steel balls. As the tube rotates, the steel balls are lifted, tumble and crush the clinker and cullet into a super-fine powder. The particle size can be controlled by a high efficiency air separator. No adverse impact has been reported during the processing of glass cullet in the cement plants (Chen et al. 2002). It is assumed that all the glass cullet can be used for blending with the clinker, and hence, no loss was considered in this study. The study estimated that about 25 kWh electricity is needed to produce 1 tonne cullet (with size less than 4mm), and no additional energy input is required to grind the cullet to powder as it is grinded together with the clinker. The average energy consumption for mixing and blending of the materials to produce 1 tonne of blended cement is 48 kWh (Zhang et al. 2014) (Table 6-3).

All the above stages (e.g. collection and processing related energy and emissions) are considered as induced impacts. Additionally, the average transport distance between the glass collection points to refuse transfer stations and then to landfill sites, as well as the environmental impact associated with the landfilling of waste glass bottles were considered as avoided impact, as the marginal technology of waste glass management is landfill disposal in Hong Kong. The data was modeled by the SimaPro 8.1.0 software.



[OPC, Ordinary Portland cement; PFC, Portland fly ash cement; Eco-GC, Eco-glass cement; FA, Fly ash]

Figure 6-1 - System boundary and framework for cement production by adopting the proposed strategies

6.2.4 Life cycle inventory analysis and impact assessment

The Life cycle inventory (LCI) analysis involves the detailed compilation and quantification of all the inputs and outputs for a product throughout its life cycle. The environmental impacts can be assessed by different environmental indicators such as the global warming potential (GWP) as climate impacts, cumulative energy requirements as energy resource consumption and others for sustainability assessment (Cucek et al. 2012). Based on the global concern, two important mid-point indicators, including GWP and total non-renewable energy consumption were assessed by SimaPro 8.1.0 software using the IMPACT 2002+ method. The method is one of the feasible and widely used environmental impacts assessment methodologies, which combined midpoint/damage approach, linking all types of life cycle inventory results via several midpoint categories to several damage categories. It contains 15 mid-point indicators (e.g. global warming potential, non-renewable energy consumption, human toxicity, acidification, etc.) for assessing the environmental impacts and 4 end-points (e.g. human health damage, ecosystem damage, climate change and resource damage) for assessing the damages (more information can be found in Humbert et al. 2012). To conduct a complete and comprehensive LCA study on different types of cement production, a full set of data for various primary materials, energy, transport, products and secondary materials are needed. In compliance with the requirement for first-hand data, various literature sources mainly from Hong Kong and mainland China have been used. The raw materials used and their transportation data are shown in Table 6-2, and a list of data used for energy, process calculations are presented in Table 6-3. The required upstream data (e.g. electricity generation, fuel production and consumption, transportation of materials, etc.) were collected from various data sources such as the China Light and Power (CLP), the Chinese Life cycle Database (CLCD), Ecoinvent database and the USLCI database.

Table 6-2 -Raw materials and transport data for cement manufacturing in Hong Kong

Materials	Exported from	Transport type	Distance (km)
Limestone	Guangdong, China	Inland barge	250[a]
Limestone	South Japan	Ocean ship	3202[a]
Sand	Guangdong, China	Inland barge	250[a]
Clay	Guangdong, China	Inland barge	250[a]
Iron ore	South Japan	Ocean ship	3,202[a]
Gypsum	Local (Power plant)	Trucks (18t)	7[b]
Limestone (for limestone powder)	Philippines	Ocean ship	1720.5[b]
Coal	Indonesia	Ocean ship	4073[b]
Fly ash to plant	Local	Truck (30t)	6[b]
Waste glass bottles	Locally generated	Truck (18t)	55[b]
Waste glass bottles to landfill sites	Locally generated	Truck (18t, 30t)	41[c]

[a] Zhang et al. (2014); [b] Measured; [c] Hossain et al. (2016b)

Table 6-3 - Sources of energy for materials/processes for cement manufacturing

Materials/processes	Energy requirement	Upstream data
Limestone production	R *	USLCI 2012b
Sand production	R *	Ecoinvent 2013g
Clay production	R *	Ecoinvent 2013b
Iron ore production	R *	Ecoinvent 2013e
Gypsum production	R *	Ecoinvent 2013d
Limestone powder processing (crushing and grinding for making powder)	3.51 kWh/t limestone [a]	CLP 2014; CLCD 2010c
Coal production and transport to cement plant in Hong Kong	R *	Hossain et al. 2016a
Electricity consumption (crushing, raw materials grinding and clinker production)	87 kWh/t clinker [b]	CLP 2014; CLCD 2010c
Coal combustion during calcinations in plant in Hong Kong	R *	Hossain et al. 2016a
Cement blending	48 kWh/t cement [b]	CLP 2014; CLCD 2010c
Transport, road	R *	CLCD 2010e
Transport, sea (Inland barge)	R *	CLCD 2010a
Transport, sea (Ocean ship)	R *	USLCI 2012e
Waste glass processing	25 kWh/t glass cullet [c]	CLP 2014; CLCD 2010c
Waste glass landfilling	R *	ELCD 2013

R* directed to the databases; [a] Choate (2003); [b] Zhang et al. (2014); [c] Measured

6.2.5 Selection of locally produced bio-fuel as co-fuel

Wood pellets derived from wood wastes are a good source of biomass for co-firing with fossil fuels due to their high energy density (Zhang et al. 2010). Our previous study showed that wood wastes generated from construction and demolition activities and other wood products are suitable for the production and use as bio-fuels based on their physical and chemical properties (Hossain et al. 2016a). The study estimated that about 184 g of coal (with 90% efficiency) is required to produce 1 kWh of heat, whereas about 226.42 g of wood pellets (with 80% efficiency) is required to produce the same amount of heat. In addition, the study estimated that about 4.53 MJ of total energy was required to generate 1 kWh of heat from coal, whereas about 1.17 MJ energy was required from wood pellets produced from locally generated wood waste (with the system boundary of heat generation in the cement industry in Hong Kong). Consequently, about 0.33 kg of CO_2 eq GHGs emission was associated with coal, while only 0.06 kg of CO_2 eq GHGs emission was associated with wood pellets for the same amount of heat generation (Hossain et al. 2016a). It may thus a good potential to use wood pellets produced by recycling local wood wastes as an alternate fuel in the cement industry in Hong Kong. With the use of wood pellets to substitute coal, it is possible to save about 3.36 MJ of non-renewable energy (considered as energy saving factor, ESF) and reduce 0.27 kg CO_2 eq GHGs emissions (considered as carbon reduction factor, CRF) for 1 kWh of heat generation.

Two equations are proposed to quantify the eco-efficiency of using wood pellets to replace coal in terms of energy consumption and GHGs emissions reduction (based on the substitution of certain percentages of coal by wood pellets) as follows;

$$\text{Energy saving (\%)} = \frac{\dfrac{\text{ESF} \times \text{\% of replacement (coal energy)}}{3.6}}{\text{Energy consumption per tonne of clinker production}} \times 100 \qquad (6-1)$$

$$\text{GHGs reduction (\%)} = \frac{\dfrac{\text{CRF} \times \text{\% of replacement (coal energy)}}{3.6}}{\text{GHGs emission per tonne of clinker production}} \times 100 \qquad (6-2)$$

6.3 Results and discussion

The first part of this section will report the assessment results of the energy consumption and GHGs emissions of various types of cement production in Hong Kong, and the second part will describe the results on assessing the possible reduction of energy and GWP impacts by adopting the proposed strategies.

6.3.1 Life cycle energy and GHGs emission for different types of cement manufacturing

The summary of the total GHGs emission and energy consumption for 1 tonne of clinker production in Hong Kong is shown in Table 6-4. In cement manufacturing, the clinker production is an important step, although it is an intermediate product. The results show that about 1025 kg CO_2 eq GHGs is emitted which consumes about 5568 MJ non-renewable energy for the production of 1 tonne of clinker. According to Zhang et al. (2014), about 551 kg CO_2 eq/t clinker is directly emitted during calcination in the Hong Kong cement plant (which accounts for 54% of the total GHGs emission for clinker production). In addition, about 35% of GHGs emission is associated with burning coal, 5% with electricity consumption, and 6% with other raw materials. Moreover, about 70%, 18% and 12% of the total energy is consumed due to the production and transport of coal, electricity consumption and the production and transport of other raw materials, respectively.

Table 6-4 -Life cycle energy consumption and GHGs emission for 1 tonne clinker production

Materials	Processes	GHGs emission (kg CO_2 eq)	Energy consumption (MJ)
Limestone	Quarrying, processing and transport to plant	54.11	624.79
Sandstone	Quarrying, handling and transport to plant	1.24	14.86
Clay	Quarrying, handling and transport to plant	1.12	13.60
Iron ore	Quarrying, processing and transport to plant	1.97	18.04
	Production, processing and transport to plant	29.38	3868.40
Coal	Coal combustion for clinker production	331	
	CO_2 emission during calcinations (decomposition of limestone)	551	
Electricity consumption	Processing (crushing, mixing, etc)	54.81	1028.34
Total		*1024.63*	*5568.03*

In addition to clinker, other additional materials such as gypsum, fly ash, limestone powder and glass cullet were used for cement production. The total energy consumption and GHGs emission for the additional materials and processes are given in Table 6-5. The results show that the avoided impacts due to avoiding landfill disposal of waste glass are quite significant compared to producing glass powder.

Table 6-5 -Total energy consumption and GHGs emission for additional materials

Materials/ Processes	Processes	GHGs emission (kg CO_2 eq)	Energy consumption (MJ)
Gypsum (1 kg)	Gypsum production and transport from desulfurization of hard coal flue gas	0.12	0.50
Limestone powder (1 kg)	Quarrying, crushing, grinding and transport to plant	0.04	0.56
Glass cullet from waste glass bottles (1 kg)	Waste glass collection, transport and processing (e.g. crushing, grinding and sieving) for making cullet	0.05	0.76
	Avoided impacts due to collection, transport and landfill	-0.03	-0.45
Fly ash (1 kg)	Induced impacts of FA due to collection, transport to plant and processing	0.006	0.11
Final processing (1 t cement)	Electricity consumption for processing (e.g. cement mixing, blending, etc)	30.24	567.36

6.3.1.1 Comparison of different types of cement (equal 28 days strength)

According to the compositions of different types of cement manufactured in Hong Kong (Table 6-1), the calculated net GHGs emission and total energy consumption are shown in Figure 6-2. With equal compressive strength at 28 days, the results reveal that compared to the OPC, Eco-GC-1 reduces 2% of the total GHGs emission with 2% saving of the total energy consumption.

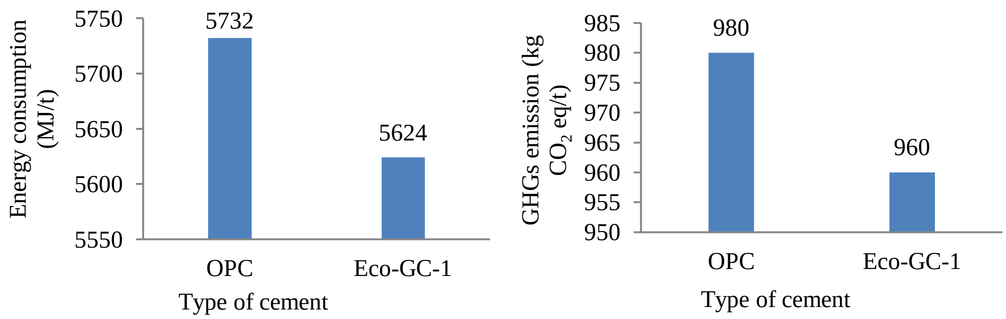


Figure 6-2 - Environmental impacts of different types of cement manufacturing (equal 28 days strength)

6.3.1.2 Comparison of different types of cement (equal 90 days strength)

It has already been mentioned that an Eco-GC-2 is proposed in this study. The experimental results revealed that compressive strength of Eco-GC-2 was slightly lower than the OPC and PFC at 28 days. However, the strength of Eco-GC-2 was comparable (even higher than OPC) at 90 days (Figure 6-3).

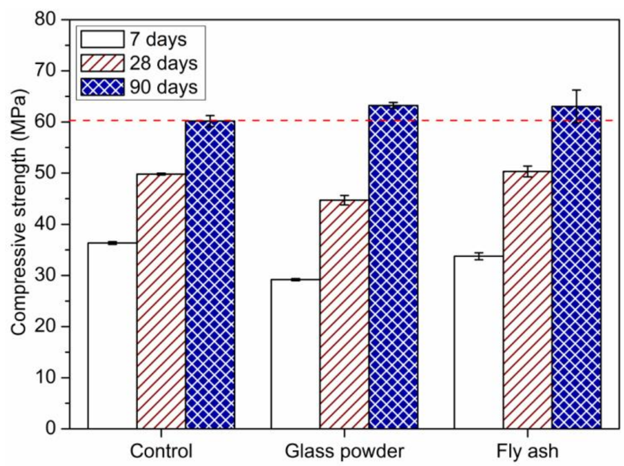


Figure 6-3 - Compressive strength of mortars prepared with glass powder and fly ash (20% OPC clinker replacement)

Based on the composition of OPC, PFC and Eco-GC-2, the comparative environmental impacts are shown in Figure 6-4. The LCA results reveal that about 16% lower energy was required with a saving of 18% GHGs emission for the production of PFC than OPC. Similarly, about 16% energy consumption and 17% GHGs emission can be potentially saved for the production of Eco-GC-2 when compared to that of OPC production. In addition, non-renewable energy consumption and GWP impacts of PFC and Eco-GC-2 production are almost similar (variation is less than 1%). However, a significant amount of waste glass can be utilized for producing Eco-GC-2 that can save landfill space, which is very important in land-scare regions like Hong Kong.

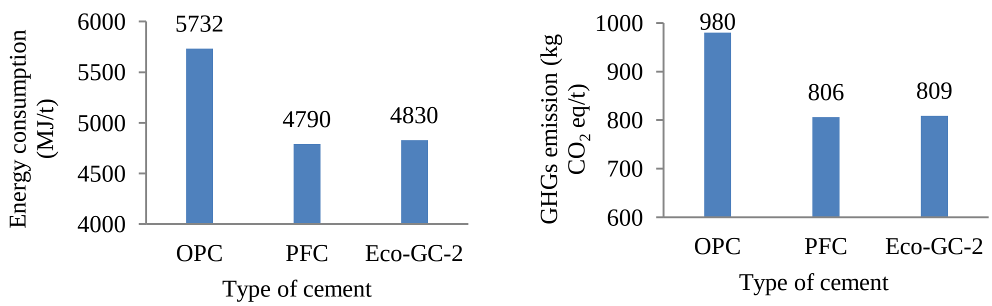


Figure 6-4 - Environmental impacts of different types of cement manufacturing (equal 90 days strength)

6.3.1.3 Comparison with other studies

The sustainability assessment of cement production may vary considerably from regions to regions (Huntzinger and Eatmon 2009). Compared to other countries, the total GHGs emission for OPC manufacturing in Hong Kong is significantly higher, but the total energy consumption is comparable (Table 6-6). About 14% higher GHGs emission (about 980 kg CO_2 eq/t) is found for this study than the average GHGs emission for OPC production in other countries (about 840 kg CO_2 eq/t). This is due to the need to import of raw materials and burning coal as fuel. Therefore, the reduction of GHGs emission for cement production in Hong Kong is needed for ensuring sustainable construction.

Table 6-6 - Comparisons of GHGs emissions and energy consumption for cement production by different studies

Study	Location	Types of cement	Energy consumption (MJ)	GHGs emission (kg CO_2 eq)	System boundary
Li et al. 2015	China	OPC	N.S	799	Cradle-to-gate
Li et al. 2015	Japan	OPC	N.S	779	Cradle-to-gate
Garcia-Gusano et al. 2015	Spain	OPC	N.S	799	Cradle-to-gate
Feiz et al. 2014	Switzerland	OPC	N.S	779	Cradle-to-gate
Marceau et al. 2006	USA	OPC	4800	929	Cradle-to-gate
Josa et al. 2007	EU	OPC	N.S	920	Cradle-to-gate
Chen et al. 2010a	France	OPC	N.S	782	Cradle-to-gate
Strazza et al. 2010	Italy	OPC	6170	769	Cradle-to-site
Bushi and Meil 2014	Canada	OPC	6620	950	Cradle-to-gate
Bushi and Meil 2014	Canada	PLC	6020	850	Cradle-to-gate
Huntzinger and Eatmon 2009	USA	OPC	N.S	880	Cradle-to-gate
Crossin 2012	Australia	OPC	N.S	850	Cradle-to-gate
This study	Hong Kong	OPC	5732	980	Cradle-to-gate
This study	Hong Kong	PFC	4790	806	Cradle-to-gate

N.S, Not specified; PFC, Portland fly ash cement; PLC, Portland-limestone cement

6.3.2 Sensitivity analysis

The sensitivity analysis due to the uncertainty of input data with the particular case study has been conducted, as the LCA results may be affected by various uncertainties such as uncertainty due to input data, and uncertainty due to choices, spatial and temporal variability (Beccali et al. 2010; Bjorklund 2002). Therefore, a sensitivity analysis was conducted in order to analyze the influence of input parameters on the LCA outcomes by calculating different scenarios, which included;

Base scenario: LCI data for principal raw materials of clinker production, such as limestone, sand, clay, and iron ore production that have been collected from USLCI (2012a), Ecoinvent (2013a), Ecoinvent (2013b), and Ecoinvent (2013c), respectively.

Alternative scenario: LCI data for limestone, sand, clay, and iron ore production have been collected from CLCD (CLCD 2012a-d).

The results of sensitivity analysis due to different input data for the production of different types of cement are shown in Figures 6-5 and 6-6. The results show that the variations of GWP and non-renewable energy consumption for different cement production are insignificant (about 1%). This is because only 12% of the total energy consumption is associated with the raw materials for clinker production, whereas about 88% is associated with the production and transport of coal and the electricity consumption. Similarly, only 6% of the total GHGs emission is associated with clinkers' raw materials production and transport, whereas the rest of the amount is associated with the calcinations process, coal combustion and electricity consumption. Therefore, it can be concluded that the results may be affected at the material level, but does not affected the results of cement production significantly.

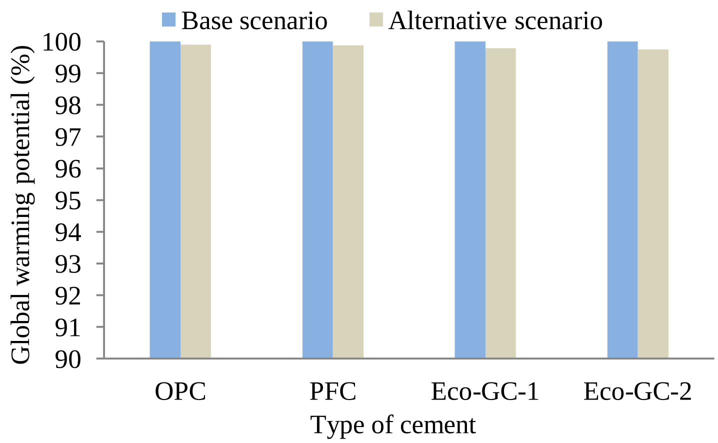


Figure 6-5 - Comparison of GWP at different scenarios

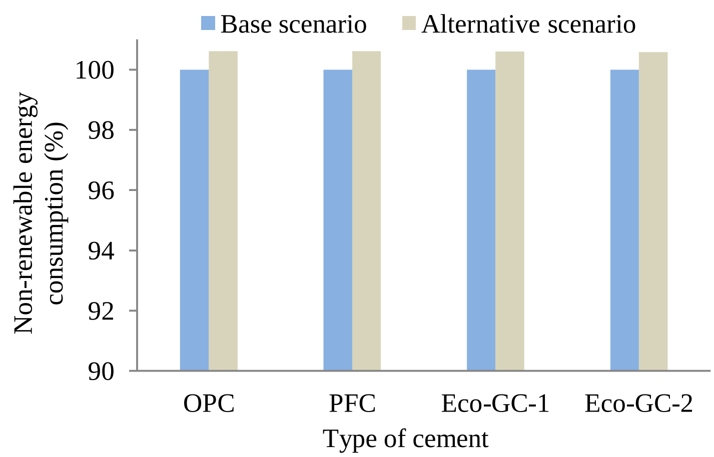


Figure 6-6 - Comparison of total energy consumption at different scenarios

6.3.3 Potential strategies for impacts reduction

This section describes the potential reduction of energy consumption and GWP impact from cement manufacturing due to the use of the proposed strategies.

6.3.3.1 Use of waste glass

One of the possible strategies for reducing environmental impacts of cement manufacturing will be the use of glass cullet derived from crushing and milling of waste glass bottles. This can also be considered as a breakthrough solution for managing waste glass in Hong Kong, as the waste disposal outlet will be exhausted soon in Hong Kong. The LCA results showed that significant energy consumption and GHGs emission could be reduced for producing the proposed Eco-GC-2 (already described at section 6.3.1.2).

6.3.3.2 Use of bio-fuel as co-fuel

In this study, the LCA results showed that about 5,732 MJ of energy is required and this emits 980 kg CO_2 eq GHGs for producing 1 tonne of OPC in Hong Kong. About 64% (3,559 MJ) of the total energy and 32% (332 kg CO_2 eq) of the total GHGs emission is associated with coal combustion in the cement plant. Based on the assessment results (mentioned in Tables 6-4 and 6-5) and by using Equations 6-1 and 6-2, an illustration of the reduction in the environmental impacts of OPC production is shown in Figure 6-7. The results show that about 2.76-13.57% of the total GHGs emissions can be potentially reduced for per tonne OPC manufacturing by replacing 10-50% of coal with the bio-fuel produced from locally generated wood wastes. Similarly, about 5.81-28.98% non-renewable energy consumption can potentially be reduced for adopting the same amount of wood wastes as a co-fuel (Figure 6-7).

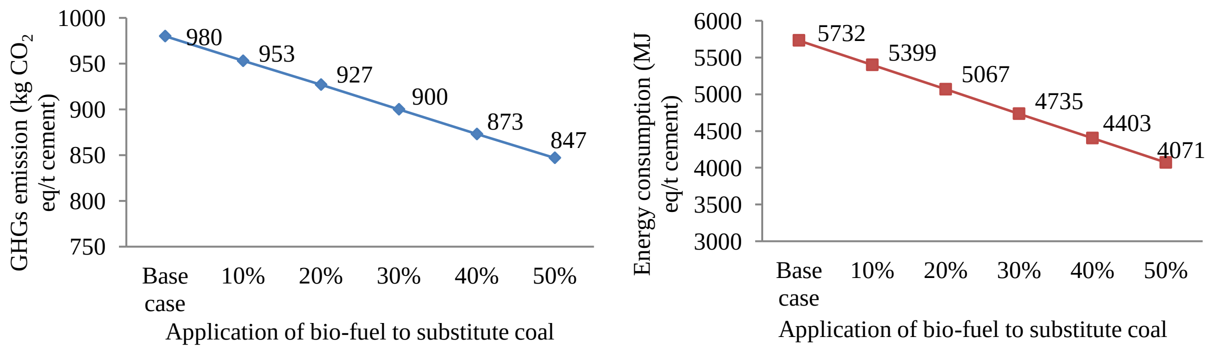


Figure 6-7 - Impacts reduction potential for OPC manufacturing

6.3.3 Application of combined strategies

When adopting the above mentioned combined strategies, significant impact reductions are possible for cement manufacturing. An illustration of the potential reduction of annual GHGs emission from the cement industry in Hong Kong is given in Table 6-7 and Figure 6-8. The estimation is based on the current rate of OPC production. The figure shows that about 2.48-12.4% of the total GHGs emissions can be saved for recycling and re-utilizing of 10-50% of the yearly generated concerned waste materials (both waste glass and wood wastes) in cement manufacturing. It is noted that only 26% of the coal used can be substituted when 50% of the locally generated wood wastes are recycled to produce the wood pellets.

For non-renewable energy consumption, approximately 3.05-15.2% of the total level can be reduced by adopting 10-50% of the locally generated waste materials (both waste glass and wood wastes) in cement production. In Table 6-7, the potential reduction of annual GHGs emission from the cement industry in Hong Kong due to the reuse of 10-50% yearly generated waste glass and wood waste as raw material and fuel have been provided as an example. The benefits will be correspondingly increased with increasing the reuse rate of these waste materials in the cement industry.

Table 6-7 - Potential GHGs emission reduction for adopting the proposed strategies in cement industry

Percentage of material*	Strategies		Total savings (t CO_2 eq/y)
	Waste glass (t CO_2 eq)	*Wood wastes (t CO_2 eq)*	
10	11016	23294	34310
15	16524	34940	51465
20	22033	46587	68620
25	27541	58234	85775
30	33049	69881	102930
35	38557	81528	120085
40	44065	93175	137240
45	49573	104821	154394
50	55081 **	116468 **	171549

* Reuse of yearly generated waste materials; ** Sharing of total saving (32% by waste glass and 68% by wood waste)

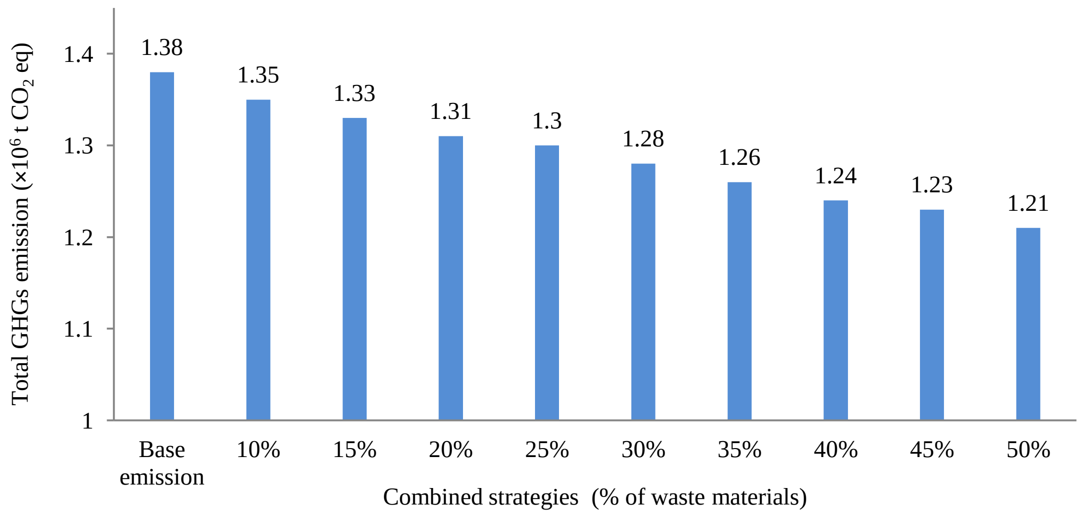


Figure 6-8 - Potential GHGs reduction for applying the combined strategies

6.4 Summary

With increasing concerns on environmental sustainability, there is a great interest to improve the sustainability of cement manufacturing. This study was conducted to assess the feasibility of improving the eco-efficiency of cement production through utilizing locally generated waste materials. The main findings of this study are summarized as follows:

(i) The production of OPC in Hong Kong is associated with a high GHGs emission.

(ii) For equal compressive strength at 28 days, the use of Eco-GC-1 in concrete reduces 2% of both energy consumption and GHGs emission when compared with pure OPC.

(iii) The use of glass cullet to produce Eco-GC-1 reduces about 20 kg CO_2 eq/t GHGs emission and 108 MJ/t of energy consumption when comparing with the base case.

(iv) For equal compressive strength at 90 days, using glass cullet to substitute 20% clinker reduces about 16% energy consumption and 17% GHGs emission when compared with the base case.

(v) When adopting the combined strategy (using both waste glass cullet to substitute clinker and waste wood as a co-fuel), over 170000 t CO_2 eq GHGs emissions can be reduced annually.

Therefore, the use of waste materials in cement production not only reduces energy and GWP impacts from the cement industry, it also can be an important outlet for waste utilization to alleviate the severe waste management problem. The proposed approaches can be regarded as the effective measures for resource-efficient and low-carbon cement production. Considering the environmental benefits for the recycling of waste glass and wood waste and their potential utilization in the cement industry, it is necessary to strengthen the policy aspects, particularly on the procurement policy of recycled materials to ensure sustainable resource management, as there is no policy regarding the use of bio-fuel derived from wood waste and waste glass is available in Hong Kong currently.

CHAPTER 7

ENVIRONMENTAL IMPACT DISTRIBUTION METHODS FOR SUPPLEMENTARY CEMENTITIOUS MATERIALS

7.1 Introduction

Since environmental sustainability is a paramount concern in the modern era, the production of environmentally benign products are encouraged in nearly all industrial sectors. As one of the major greenhouse gases (GHGs) emission intensive industries, the construction industry is responsible for significant environmental problems and natural resources depletion (Kim et al. 2013; Cabeza et al. 2014). Consequently, the development of sustainable construction materials is in high demand (Saghafi andTeshnizi 2011; Wu et al. 2014c). Life cycle assessment (LCA), a well-established technique specified in international standards (ISO 2006a,b), has been extensively used to evaluate environmental impacts and serves as a decision support tool in both the business and political levels (Dong et al. 2015).

Concrete is one of the most commonly used construction materials. The annual consumption rate of concrete is around 25 gigatonnes globally (over 3.5 tonnes per capita) (Gursel et al. 2014). The production of cement, a key component of concrete, has attracted much attention in the LCA area, due to its production process is energy intensive and produces huge amounts of GHGs (Zhang et al. 2013; Shen et al. 2015). Worldwide, the cement industry contributes to 5-10% of the total anthropogenic GHGs emissions (Scrivener and Kirkpatrick 2008), and 12-15% of total industrial energy use (Madlool et al. 2011). The environmental consequences of cement manufacturing can be local, regional or global in scale (Huntzinger and Eatmon 2009). Besides contributing to global CO_2 emission, the cement production process also generates SO_2 and NO_x which are considered as regional environmental impacts, and dust emissions as a local impact

(Van den Heede et al. 2012). The cement industry is also blamed for its global impacts of depleting non-renewable resources such as fossil fuels, limestone and clay.

To date, due to increasing sustainability concerns in the construction sector and to produce more durable concrete, it has been a common practice to produce concrete with cement replacements by the so-called supplementary cementitious materials (SCMs). SCMs are originally generated as industrial wastes or by-products. The most commonly used SCMs are fly ash (FA), granulated blast furnace slag (GBFS) and silica fume (SF). They are widely used in blended cement (Li et al. 2016b; Abdalqader et al. 2016; Krishnan et al. 2015; Guynn and Kline 2015), concrete batching (Flower and Sanjayan 2007; Habert et al. 2011; De Schepper et al. 2014; Gonzalez-Fonteboa and Martinez-Abella 2008; Zhang et al. 2014; Safiuddin et al. 2015; Torgal et al. 2012; Teixeira et al. 2016) and concrete products (Kou and Poon 2013; Poon and Chan 2006b).

SCMs are in fact sourced from waste materials. When recycled and reused, they would not be landfill disposed of and its associated environmental impacts can be avoided, and this can also save the use of non-renewable resources. As such, their status in LCA has been changed from wastes to by-product or co-product and their environmental impacts should then be accounted for and allocated in the LCA methodology (Chen et al. 2010b).

Until now, three types of allocation approaches have been employed for assessing the environmental impacts of concrete products produced with SCMs (Van den Heede and De Belie 2012). These are allocation by mass value, economic allocation and no allocation (considered as waste and allocation is avoided). As the status of SCMs is no longer considered as wastes, therefore, the first two allocation approaches are preferred. However, these allocation approaches are not used in all LCA practices. This is because the environmental impacts of concrete or concrete products incorporating SCMs are much higher than the normal concrete or concrete products using only conventional Portland cement as the binder (Chen et al. 2010b; Hossain et al. 2016c). Therefore, conflicts between the practitioners and the researchers in terms of choice of allocation approaches occur as it is impractical and unreasonable to the practitioners to declare concrete or concrete products produced with SCMs to have higher environmental impacts.

In this study, a comprehensive review is first presented in order to evaluate the current situation on the selection of different LCA approaches in the field of cement and concrete production when SCMs are involved. This is followed by analyzing the appropriateness of using multi-functional modeling approaches of SCMs. A case study on assessing SCMs and concrete in Hong Kong is conducted to corroborate the assessment.

7.2 Literature review

In LCA, allocation means the partition of input and/or output flows of a process to the product system, or simply, the partition of the environmental impacts according to the ratio of mass or economic value between the product and the by-product(s). The environmental impacts distribution procedure in LCA is described by the ISO 14044 standard as follows: (i) allocation should be avoided by dividing the unit process into sub-processes or system expansion, if possible, or (ii) allocation should be partitioned based on the physical relationship (by mass or energetic value) among the products and co-products, or their economic functions or values [6]. On the basis of the above, two allocation procedures have been proposed including allocation by mass value (called mass allocation), and allocation by economic value (called economic allocation) (Chen at al. 2010b; Van den Heede and De Belie 2012). Allocation by mass refers to the division of environmental impacts according to the mass ratio of the main product and by-products, whereas the partition of the environmental impacts based on the economic value is called economic allocation. Besides the above two approaches, no allocated impacts of SCMs have been considered by some researches as SCMs are recycled and reused in cement or concrete as constituents to replace natural materials (Flower and Sanjayan 2007; Boesch and Hellweg 2010).

However, according to the Directive of the European Union, a substance or object can be regarded as a co-product or by-product (rather than waste), if it fulfills the following conditions: (i) its further use is certain, (ii) it can be used directly without any further processing other than normal industrial practices, (iii) it is produced as an integral production process, and (iv) it will not lead to adverse environmental or human health impacts (EU Directive 2008). As SCMs (e.g. FA, GBFS and SF) fulfill the conditions indicated above, SCMs should belong to by-products and the environmental impacts of producing their main products should be allocated to them when SCMs are used in concrete or concrete products. However, according to ISO (ISO 2006b), allocation should be avoided by applying the system expansion approach. In the literature, several LCA studies on environmental impact assessment have been conducted on concrete or concrete product production using SCMs. Table 7-1 lists these LCA studies using different approaches and Table 7-2 presents the details of the methodological aspects of these LCA studies.

Table 7-1 – LCA studies on the application of SCMs in construction using different approaches

Reviewed literature	Type of SCMs	Application	Country	Allocation approach			System expansion
				No allocation	*Mass allocation*	*Economic allocation*	
Flower and Sanjayan 2008	FA, GBFS	Concrete	Australia	*			
O'Brien et al. 2009	FA	Concrete	Australia	*			
Habert and Roussel 2009	FA, GBFS	Concrete	France	*			
Chowdhury et al. 2010	FA	Road construction	USA	*			
Chen et al. 2010b	FA, GBFS	Comparison of SCMs with cement	France	*	*	*	
Habert et al. 2011	FA;GBFS: SF	Concrete	France	*	*	*	
Hajek et al. 2011	SF	Concrete	Czech Republic	*			
Van den Heede and De Belie 2012	FA, GBFS	Comparison: SCMs & cement; different LCA methods	Belgium		*	*	
Park et al. 2012	FA, GBFS	Concrete	South Korea	*			
Crossin 2012	FA;GBFS;SF	Concrete blend	Australia			*	*
Proske et al. 2013	FA, GBFS	Concrete	Germany	*		*	
Knoeri et al. 2013	FA	Concrete	Switzerland	*			
De Schepper et al. 2014	FA	Concrete	Belgium			*	
Randl et al. 2014	FA, GBFS	Concrete	Austria	*			
Van den Heede and De Belie 2014	FA	Concrete	Belgium			*	
Zhang et al. 2014	FA	Concrete	Hong Kong	*			
Blankendaal et al. 2014	FA, GBFS	Concrete	Netherland	*			
Seto 2015	FA	Concrete	Canada	*	*	*	
Liu et al. 2015	FA	Concrete	China	*			
Turk et al. 2015	FA	Concrete	Slovenia	*			
Saade et al. 2015	GBFS	Cement	Brazil		*	*	*
Anastasiou et al. 2015	FA; GBFS	Concrete	Greece	*		*	
Celik et al.2015	FA, LC	Concrete	USA	*			
Crossin 2015	GBFS	Concrete	Australia				*
Berndt 2015	FA, GBFS	Concrete	Australia	*			
Lawania et al. 2015	FA, GBFS	Concrete wall	Australia	*			
Li et al. 2016b	GBFS	Cement	China		*	*	
Hossain et al. 2016c	FA	Concrete paving eco-blocks	Hong Kong	*	*		
Pushkar and Verbitsky 2016	FA; GBFS	Blended cement	Israel	*	*	*	
Teixeira et al. 2016	FA	Concrete	Portugal			*	

FA, Fly ash; GBFS, Granulated blast furnace slag; SF, Silica fume; LC, limestone powder

Table 7-2 - Details of methodological aspects of LCA studies on concrete/concrete products

Reviewed literature		System boundary			Life cycle inventory data			Impact categories													
	Functional unit	Cradle-to-gate	Cradle-to-site	Cradle-to-grave	Primary data	Database	Literature	Global warming	Energy consumption	Acidification potential	Eutrophication potential	Ozone depletion potential	Respiratory impacts	Abiotic depletion	Human toxicity	Freshwater aquatic ecotox.	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Water consumption	Land use
Flower and Sanjayan 2007	$1m^3$		*		*		*	*													
O'Brien et al. 2009	$1m^3$	*	*			*	*	*												*	
Habert and Roussel 2009	$1m^3$						*	*													
Chowdhury et al. 2010	1kg	*				*	*	*	*	*					*	*					
Chen et al. 2010b	1kg	*				*	*	*	*	*	*	*		*	*	*	*	*	*		
Habert et al. 2011	$1m^3$	*				*	*	*		*	*	*		*	*	*	*	*	*		
Hajek et al. 2011	$1m^3$			*	*	*	*	*	*	*									*	*	
Van den Heede and De Belie 2012	1kg	*				*	*	*	*	*	*			*	*				*		
Park et al. 2012	$1m^3$	*			*	*	*	*													
Crossin 2012	$1m^3$			*	*	*	*	*	*												
Proske et al. 2013	$1m^3$	*				*	*	*													
Knoeri et al. 2013	$1m^3$		*		*	*	*	*	*	*	*	*	*			*					*
De Schepper et al. 2014	$1m^3$			*		*	*	*		*	*	*		*	*	*	*	*	*		
Randl et al. 2014	$1m^3$	*					*	*	*	*	*										
Van den Heede and De Belie 2014	$1m^3$			*		*	*	*													
Zhang et al. 2014	$1m^3$		*		*	*	*	*													
Blankendaal et al. 2014	$1m^3$			*	*	*	*	*		*	*	*	*		*	*	*	*	*		*
Seto 2015	$1m^3$			*		*	*	*		*				*						*	
Liu et al. 2015	$1m^3$	*					*	*													
Turk et al. 2015	$1m^3$	*			*	*	*	*		*	*			*					*		
Saade et al. 2015	1t	*				*	*	*		*	*	*		*	*	*	*	*	*		
Anastasiou et al. 2015	1km			*	*		*	*													
Celik et al. 2015	$1m^3$		*				*	*		*	*		*								
Crossin 2015	$1m^3$			*	*	*	*	*													
Berndt 2015	$1m^3$		*	*		*	*	*													
Lawania et al. 2015	$1m^3$	*		*	*	*	*	*	*												
Li et al. 2016b	1kg	*			*	*	*	*		*	*			*	*				*		*
Hossain et al. 2016c	1t		*		*	*	*	*	*	*	*	*	*								
Pushkar and Verbitsky 2016	$1m^3$	*				*	*	*		*					*						
Teixeira et al. 2016	$1m^3$	*			*	*	*	*		*	*	*		*					*		

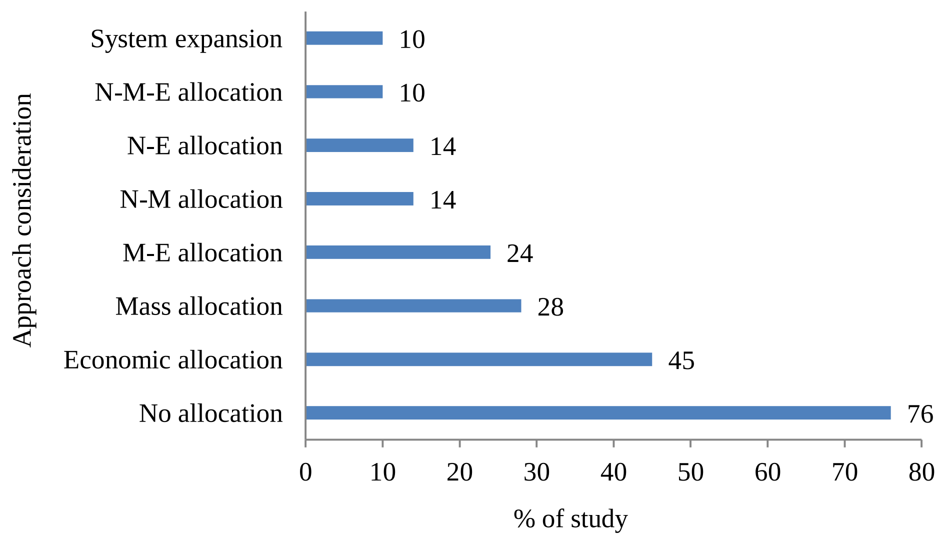
Pushkar and Verbitsky (2016) reported the environmental impacts of producing different concrete mixtures using blended cement (e.g. cement produced with FA, GBFS and limestone powder). Different allocation approaches were adopted to show the variation of the results, and they found that SCM concretes had about 15-55%, depending on the types of SCMs used, higher environmental loads than the ordinary Portland cement (OPC) concrete. Hossain et al. (2016c) assessed the environmental impacts of concrete paving block production using recycled aggregates, FA and cement, and they found that about 60% higher respiratory effects, 30% higher GHGs emission, and 38% higher non-renewable energy consumption when mass allocation was adopted.

Chen et al. (2010b) conducted a comparative study on environmental impacts between SCMs (FA and GBFS) and cement using different application approaches. When mass allocation was selected, it was found that when compared to OPC, about 165% and 495% higher global warming effect was associated with the use of GBFS and FA, respectively. The corresponding energy consumption was 346% and 744%, respectively for GBFS and FA. Similar results were found for cement product using GBFS by Li et al. (2016b) and concrete production by Habert et al. (2011). All the reported studies demonstrated that very high environmental impacts were associated with concrete or concrete products using SCMs when the mass allocation approach was adopted. However, when the economic allocation approach was used, inconsistencies were found amongst different impacts (De Schepper et al. 2014; Chen et al. 2010b; Turk et al. 2015; Saade et al. 2015).

Weidema and Schmidt (2010) stated that the system expansion approach can ensure mass and energy balance, whereas the allocation approach nearly always fails to do so. In the system expansion approach, an assessment is required on the systems which are likely to be affected by the use of SCMs: namely OPC production, when SCMs are considered as by-products (Crossin 2015). This is because the system boundary is expanded to include additional system processes which are affected by the co-producing processes.

Selection of an appropriate approach is one of the most important methodological aspects in LCA (Weidema and Schmidt 2010; Gursel 2014; Suh et al. 2010). There is no consensus on any specific method (Finnveden et al. 2009), and the selection of the allocation approach has been mostly related to the study objective, as well as individual preferences. This review summarized the findings of the recent LCA studies pertaining to concrete or concrete products production using SCMs since 2007 (Table 7-1). A summary of the choice of different approaches is presented in Figure 7-1.

The review indicates that most of the studies (about 76%) selected “no allocation” in the assessments associated with SCMs, and hence resulted in lower environmental impacts when compared with that of OPC. Economic allocation was selected by about 45% of the reviewed studies. This is mainly due to the lower impacts associated with SCMs when the economic allocation was adopted (Chen et al. 2010b). However, only a few studies have used the system expansion approach for assessing SCM concretes. For example, Saade et al. (2015) assessed cement production and Crossin (2015) assessed GBFS concrete through applying the system expansion method, but the studies did not provide any conclusions on selection preference of the modeling approach. In addition, detailed studies on the application of FA and SF using the system expansion approach are yet to be conducted.



N-M-E, Combined no (without), mass and economic allocation; N-M, combined no and mass allocation; N-E, combined no and economic allocation; M-E, combined mass and economic allocation

Figure 7-1 - Percentage of studies with different approaches consideration

Although several studies have suggested using the economic allocation approach for the LCA assessment of concrete with SCMs, the price variations in the temporal and spatial scale are required to be critically evaluated. In addition, system expansion is the preferable option for ISO's (ISO 2006b) specification.

7.3 General methodology for allocation procedure

The environmental impacts of by-products or waste materials, *i*, can be expressed by the following equation:

$$B_i = [A_x . I_{mP} + (SP_i + T_i)] \qquad (7\text{-}1)$$

where B_i is environmental impacts of the by-product *i*, *A* is the allocation coefficient (allocation coefficient refers to the fraction derived from the ratio of the main product and by-products according to the their mass or economic value), *x* is the type of allocation, I_{mP} is the total environmental impact of the main product, SP_i is the environmental impacts of the secondary process (further processing to reuse) of by-product *i*, *Ti* is the environmental impacts due to the transport of the by-product *i* to the final use.

7.3.1 Allocation by mass

When mass allocation is adopted for by-product *i*, the allocation coefficient ($\emptyset_i$) can be written as follows:

$$\emptyset_i = \left[\frac{Mass_i}{(Mass_{mP} + Mass_i)}\right] \qquad (7\text{-}2)$$

where $Mass_i$ is the mass fraction of the by-product *i*, $Mass_{mP}$ is the unit mass of the main product *mP*. The environmental impact of the by-product *i* can be derived by:

$$B_{imas} = [\emptyset_i . I_{mP} + (SP_i + T_i)] \qquad (7\text{-}3)$$

7.3.2 Economic allocation

As many of the by-products have monetary values, their environmental impacts can be allocated according to the impacts of the main products. When the economic allocation is adopted for by-product *i*, the allocation coefficient ($\boldsymbol{\gamma}_i$) can be written as follows:

$$\gamma_i = \left[\frac{(Mass_i . \$_i . \varepsilon)}{\$_{mP} . \varepsilon + (Mass_i . \$_i . \varepsilon)}\right] \qquad (7\text{-}4)$$

where $\$_i$ is the unit price of by-product *i*, $\$_{mP}$ is the unit price of main product, $\mathcal{E}$ is the fluctuation index depending on geographical variations or market. The environmental impact for economic allocation of the by-product *i* can then be expressed by:

$$B_{iecon} = [\gamma_i . I_{mP} + (SP_i + T_i)] \qquad (7\text{-}5)$$

Furthermore, when the environmental impacts of different SCMs are compared, their equivalent functional or binding capacity has to be considered. Based on the EN 206-1 standard (CEN 2004), the comparison of SCMs with traditional binding material (e.g. cement, CEM I) can be expressed by using the following formula:

$$\beta = \frac{CEM\ I}{K_{SCM}} \qquad (7\text{-}6)$$

where *β* is the binding capacity of SCMs, *K* is the specific coefficient for each SCM. Therefore, the environmental impacts of the supplementary material *X* can be compared with CEM I as follows:

$$X = \left[\frac{1}{\beta} . \sum\nolimits_{CEM\ I} Env\right] \qquad (7\text{-}7)$$

The *K* parameter equals to 0.6, 0.9 and 2.6 for FA, GBFS and SF, respectively (Chen at al. 2010b; Wong and Razak 2005), which means that 1/0.6 kg of fly ash will have the same properties as 1/0.9 kg of GBFS, and 1/2.6 kg of SF and 1 kg of CEM I. Therefore, the environmental impacts of 1 kg of CEM I is compared to 1.11 kg of GBFS, 1.67 kg of fly ash, and 0.38 kg of SF in this study.

7.4 System expansion approach

System expansion is a preferred method when dealing with co-product in LCA (Weidema 2001), as this approach ensures mass and energy balances (Weidema and Schmidt 2010). In addition, ISO (ISO 2006b) also stated that allocation should be avoided through expanding the system boundary, if possible. This may be due to high uncertainties are associated with the allocations process. However, there is no agreed consensus on performing system expansion in LCA when multi-functional processes are involved (Crossin 2012). Weidema (2001) provided four general rules for expanding the boundary when dealing with co-product with complex functions (e.g. expanding the function of the co-producing process and then used in the secondary products), which are:

(i) *the co-producing process shall be ascribed fully (100%) to the determining co-product for this process (product A, e.g. determinate product),*
(ii) *under the conditions that the dependent co-products are fully utilized in other processes and actually displace other products there, main product shall be credited for the processes that are displaced by the dependent co-products. The intermediate treatment shall be ascribed to main product. If there are differences between a dependent co-product and the product it displaces, and if these differences cause any changes in the further life cycles in which the co-product is used, these changes shall likewise be ascribed to main product,*
(iii) *when a dependent co-product is not utilized fully (i.e. when part of it must be regarded as a waste), but at least partly displaces another product, the intermediate treatment shall be ascribed to secondary product, while secondary product is credited for the avoided waste treatment of the co-product, and*
(iv) *when a dependent co-product is not displacing other products, all processes in the entire life cycle of the co-product shall be fully ascribed to main product.*

The scenario of SCMs (e.g. FA, GBFS and SF) used in Hong Kong is shown in Table 7-3. Following Weidema's system expansion principles, the system expansion for SCMs considered in this study is expressed in Figure 7-2.

Table 7-3 - List the sources, production, and recycling rates of the studied SCMs in Hong Kong

SCMs	Sources	Production (million tonnes)	Recycling rate (%)	Reference
GBFS	China	21269 (2013)	85	Feng et al. 2015; Zhang et al. 2014
SF	China	4.78 (2012)	100	Ji et al. 2014
FA	Local	0.20 (2015)*	100	Chow 2015

*Local production of FA met one-third of the Hong Kong's total demand in 2015, and the rest was imported mainly from China

As FA and SF are fully recycled, environmental impacts from their main product and secondary processes should not be ascribed to concrete production using the system expansion approach (except impacts due to transportation) according to second principle of system expansion. For GBFS, the environmental impacts of the secondary processes and transport were ascribed to concrete production, and credited for avoided waste treatment (same amount of GBFS) based on the third principle of system expansion.

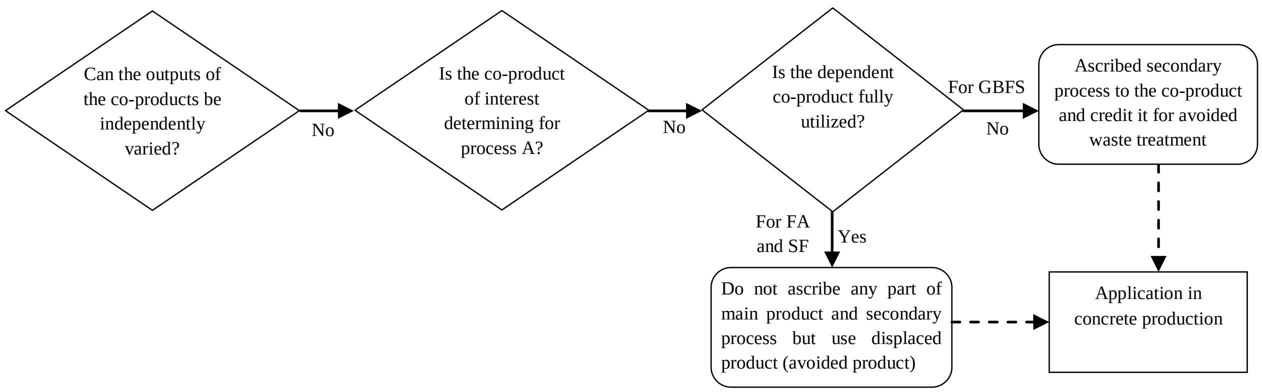


Figure 7-2 - System expansion approach for SCMs in concrete production

7.5 Case study: Environmental impacts of SCMs and concrete

Based on the different approaches, a detailed description and assessment of the environmental impacts of SCMs and concrete production in Hong Kong is provided in this section.

7.5.1 Methodology of the case study

The life cycle inventory (LCI) data for SCMs was collected from different sources and they are detailed in Tables 7-4, 7-5 and 7-6.

Hong Kong is considered as a resource-scare city, where most of the construction materials are imported from other regions or countries. The raw materials used for concrete production in Hong Kong with their import locations are presented in Table 7-5, and the energy requirements associated with their production or processing with upstream database are given in Table 7-6. In this LCA study, a cradle-to-site (e.g. concrete plants) and cradle-to-gate system boundary were considered for SCMs and concrete, respectively. The functional unit (FU) of SCMs was 1 kg SCM produced, while the FU of concrete was $1m^3$. The current market price of the raw materials was collected from a leading construction company in Hong Kong. The LCI data for aggregate production and transport was based on our previous study (Hossain 2016b), and data on cement production in Hong Kong data were collected from Zhang et al. (2014) and the Chinese Life Cycle Database (CLCD) (CLCD 2010b). Finally, the transport distance from the importing locations or production sites to the concrete batching plants in Hong Kong were identified.

In addition, data from the China Light and Power (CLP) and CLCD were used as upstream data for electricity, fuel and transportation. The CLCD database contains the LCI data for Chinese materials and processes. As the majority of the materials in Hong Kong are imported from mainland China, the use of the CLCD database would be more appropriate than other LCI databases. The scenarios of all the materials were modeled in SimaPro 8.1.5 software to include the life cycle stages of production, transport, energy requirements and fuel consumption. Four mid-point impact categories were selected based on the importance (Table 7-2) and priority for Hong Kong, and then assessed by the IMPACT 2002+ Impact Method (Jolliet et al. 2003).

Table 7-4 - Relevant background data for SCMs

Materials' cost and emission data	Relevant data	Data sources/upstream data
Pig iron price in China	3.90 HK$/kg equivalent	Li et al. 2016b
Ferrosilicon alloys price in China (FeSi, 75% Si)	9.7 HK$/kg equivalent	Metal pages 2016
Electricity price in Hong Kong	1.40 HK$/kWh	CLP 2014
FA price in Hong Kong	0.6 HK$/kg (on average)	Local construction industry
GBFS price in Hong Kong	0.6 HK$/kg (on average)	Local construction industry
SF price in Hong Kong	1.9 HK$/kg (on average)	Local construction industry
Pig iron production (emission data)	R*	Ecoinvent 2013f
Electricity generation from coal in China (emission data)	R*	Ecoinvent 2013c
Ferrosilicon alloys production (emission data)	About 8000–9000 kWh electricity and 510–530 kg of coke in China	Wang et al. 2015
Electricity generation in China (emission data)	(On average)	Li et al. 2016a
Heat generation from coke in China (emission data)	R*	Ecoinvent 2013k

* Referring to the database mentioned at the right column.

Table 7-5 - Raw materials and transport for concrete manufacturing in Hong Kong

Materials	Imported from	Transport type	Distance (km)
River sand	Extraction sites to Dongguan, Guangdong Province, China to Hong Kong Port	Trucks (30 t); Inland barge	20; 128
	Hong Kong Port to concrete batching plant *	Trucks (30 t)	30
Crushed stone	Extraction sites to Dongguan, Guangdong Province, China to Hong Kong Port	Trucks (30 t); Inland barge	50; 128
	Hong Kong Port to concrete batching plant *	Trucks (30 t)	30
Cement	Local (Green Island Cement plant to concrete batching plant*)	Trucks (30 t)	28
FA	Local (Coal-fired power plant to batching plant)	Trucks (30 t)	28
GBFS	Guangdong, China to Hong Kong Port	Inland barge	128
	Hong Kong Port to concrete batching plant *	Trucks (30 t)	30
SF	Guangdong, China	Inland barge	128
	Hong Kong Port to concrete batching plant *	Trucks (30 t)	30

* The average distance is considered due to different geographic locations

Table 7-6 - Sources of energy for materials/processes for concrete manufacturing

Materials/processes	Energy requirement	Upstream data
River sand production	R*	Hossain et al. 2016b
Crushed stone production	R*	Hossain et al. 2016b
Cement production	R *	CLCD 2010b; Zhang et al. 2014
FA	9.3 kWh/t [a]	CLP 2014; CLCD 2010c
GBFS	72.15 kWh/t [b]	CLP 2014; CLCD 2010c
GBFS landfill	R * (as inert waste)	Ecoinvent 2013j
SF	10 kWh/t [a]	CLP 2014; CLCD 2010c
Concrete (batching) production	2.5 kWh/t of concrete [c]	CLP 2014; CLCD 2010c
Transport, road	R *	CLCD 2010e
Transport, sea (Inland barge)	R *	CLCD 2010a

* Referred to the database/references; [a] MPA 2009; [b] Dunlap 2003; [c,] Zhang et al. 2014

The mix-design of the studied OPC concrete and concretes using SCMs is presented in Table 7-7. The first three concrete mix-designs were collected from the Civil Engineering and Development Department, Hong Kong SAR Government (Leung and Wong 2011) and last one was from (Berndt 2015).

Table 7-7 - Mix-design (MD) of different concrete used in this study

Materials (kg/m^3)	MD-1	MD-2	MD-3	MD-4
OPC	445	333	238	315
GBFS	0	142	237	0
FA	0	0	0	105
SF	0	0	25	0
Coarse aggregates	905	935	935	1020
Fine aggregates	745	680	605	718
Water	208	221	221	172
Admixture	1.69	1.81	2.1	1.80
Total weight (kg)	2304.69	2312.81	2263.1	2331.80
28 days compressive strength (MPa)	58.7	60.8	66	53.3

7.5.2 Results: Environmental impacts of SCMs and concrete

7.5.2.1 Calculation of allocation coefficients

The allocation coefficient for environmental impacts assessment of SCMs was calculated on the basis of the mass and economic values using Equations 7-3 and 7-5 (shown in Table 7-8). The mass ratio for GBFS and FA co-generation from Pig iron and electricity generation was obtained from Chen at al. (2010b), and the mass ratio for SF from ferrosilicon alloys was calculated from Wang et al. (2015). The price of all materials for calculating economic allocation coefficient were collected from 2014-2016.

Table 7-8 - Allocation coefficient calculation for SCMs

Characteristics	Material/Output					
	Pig Iron	*GBFS*	*FeSi*	*SF*	*Electricity*	*FA*
Mass ratio (kg)	1	0.24	1	0.23	1 kWh	0.052
Mass allocation (%)	80.65	19.34	81.30	18.70	87.59	12.41
Market price (HK$)	3.9/kg	0.6/kg	9.7/kg	1.9/kg	1.40/kWh	0.6/kg
Economic allocation (%)	96.44	3.56	95.69	4.31	97.82	2.18
Binding capacity (*β*)		0.90 [a]		2.60 [b]		0.60 [a]

[a,] Chen at al. 2010b; [b,] Wong and Razak 2005

7.5.2.2 Variation of allocation coefficients

It has been clearly shown from the review that researchers chose allocation approaches randomly without a consistent methodology in the LCA assessment of concrete incorporating SCMs. Higher impacts were recorded when the mass allocation was adopted, while lower impacts were found when the economic allocation approach was adopted. Based on the results, economic allocation was suggested to be the preferred approach by several studies (Van den Heede and De Belie 2012; Gursel 2014; Messagie et al. 2013). Since there is limited research on economic allocation approach, LCA studies have to rely on the allocation coefficient provided by a small number of studies, such as Chen et al. (2010b). However, the economic allocation coefficients vary temporally and spatially.

For example, about 1% and 2.3% economic allocation coefficient for FA and GBFS was reported by Chen et al. (2010b), while 2.18% and 3.56% economic allocation coefficients for FA and GBFS, respectively were found in this study (allocation coefficient due to economic value is consistent with other study, see Table 7-9). This is because the previous study used economic data in 2006 and 2008 for the coefficient calculation but this study obtained data from different geographic regions in the latest period (2014-2016).

Table 7-9 - Comparison of allocation coefficients

Material	**FA**		**GBFS**		**SF**	
Allocation	*Mass*	*Economic*	*Mass*	*Economic*	*Mass*	*Economic*
Chen et al. 2010b	12.40	1.0	19.40	2.30	--	--
Saade et al. 2015	--	--	19.68	3.60	--	--
This study	12.41	2.18	19.34	3.56	18.70	4.31

The present study found the economic allocation coefficient has been increased, and this correspondingly results in significant increase in the environmental impacts of SCMs. The environmental impacts of SCMs (equivalent amount of 1 kg Ordinary Portland cement) due to economic coefficient variations are given in Table 7-10.

Table 7-10 - Environmental impacts of SCMs for economic allocation

Impact category	**Chen et al. 2010b**	**This study**	**Chen et al. 2010b**	**This study**	**This study**
	FA		*GBFS*		*SF*
Respiratory inorganics (kg PM2.5 eq)	7.13E-04	1.52E-03	3.9E-04	5.11E-04	9.61E-04
Global warming (kg CO_2 eq)	0.43	0.90	0.29	0.39	0.79
Non-renewable energy (MJ primary)	4.06	8.38	3.20	4.09	9.12
Acidification (kg SO_2 eq)	0.01619	0.035	0.00590	0.00767	0.01385

7.5.2.3 Environmental impacts of SCMs for different allocation approaches

This section describes the results of environmental impact of the SCMs in terms of different allocation approaches and compared them with the equivalent amount of Portland cement.

7.5.2.3.1 Mass allocation: Based on the mass allocation coefficient mentioned in Table 7-8 and using Equation 7-3, a comparison of environmental impacts of SCMs with cement (CEM I) is presented in Figure 7-3. Equation 7-7 was used in this assessment for equivalent binding capacity of SCMs with CEM I. The results showed that about 14.65 times higher respiratory impacts, 4.12 times higher global warming impacts, 6.86 times higher non-renewable energy consumption, and 13.10 times higher acidification impacts were observed for FA compared to cement. The corresponding impacts was about 3.69, 0.96, 2.15 and 1.82 times higher for GBFS, and about 6.52, 2.38, 5.60 and 3.44 times higher for SF than cement.

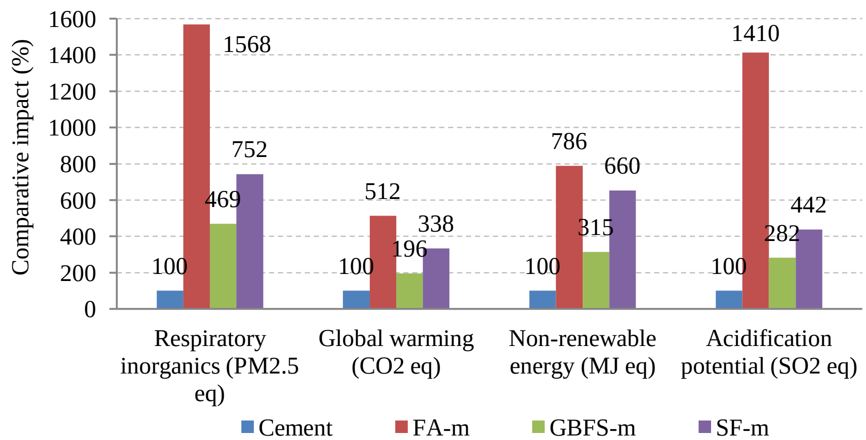


Figure 7-3 - Comparative environmental impacts of binders using mass allocation

7.5.2.3.2 Economic allocation: When economic allocation was adopted, the environmental impacts for SCMs were assessed by using Equations 7-5 and 7-7, and the comparative results are shown in Figure 7-4. The Figure shows that about 1.81, 0.44 and 1.69 times higher impacts for respiratory damage, non-renewable energy consumption and acidification impacts, respectively, while about 9% lower impact on global warming potential were observed for FA compared to that of cement. A similar trend was observed for SF. For GBFS, about 5%, 61%, 30% and 41% lower impacts in the category of respiratory effect, global warming, energy consumption and acidification were observed. Due to the lower impacts recorded for economic allocation than mass allocation, many studies used the former approach (See Table 7-1 and Figure 7-1).

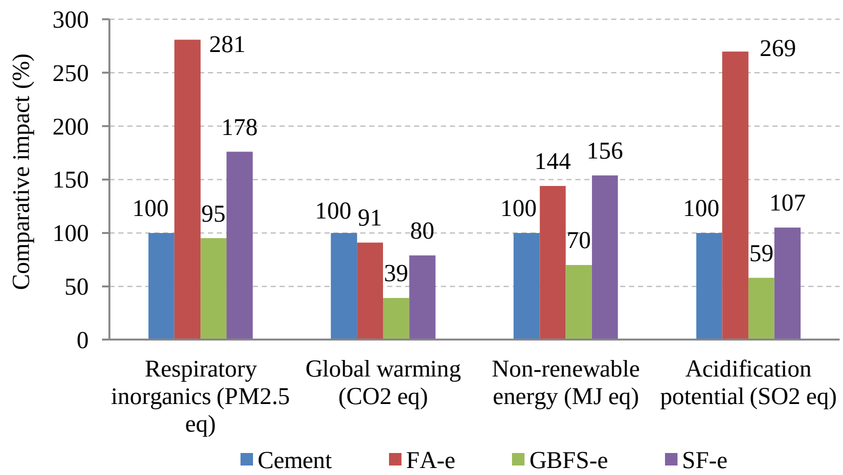


Figure 7-4 - Comparative environmental impacts of binders using economic allocation

7.5.2.4 Assessment of concrete production using different SCMs by system expansion approach

Based on the mix-design of the concrete shown in Table 7-7, the assessment results of different concrete types using the system expansion approach are shown in Table 7-11, and Figure 7-5 (an example of environmental impacts calculation of SCMs using system expansion is given in Appendix B). It can be seen that about 15%, 29% and 19% lower respiratory effect was observed for MD-2, MD-3 and MD-4 concrete, respectively than the OPC concrete (MD-1). Moreover, significantly lower impact on global warming potential was observed for concrete made with SCMs when compared to the OPC concrete. The corresponding GHGs reduction was 20%, 38% and 24%, respectively.

About 15%, 29% and 20% lower energy was consumed for the production of SCM concrete using the mix-design MD-2, MD-3 and MD-4, respectively than the OPC concrete. In addition, about 14%, 30% and 18% lower acidification impact was found for mix-design MD-2, MD-3 and MD-4, respectively compared to the OPC concrete.

The overall results indicated that significant reduction of environmental loads were observed when the system expansion approach is used for assessing concrete made with SCMs.

Table 7-11 - Environmental impacts of different types of concrete using system expansion approach

Impact category	Concrete mix-designs			
	MD-1	*MD-2*	*MD-3*	*MD-4*
Respiratory inorganics (kg PM2.5 eq)	0.33	0.28	0.24	0.27
Global warming (kg CO_2 eq)	498.76	397.42	307.16	376.90
Non-renewable energy (MJ primary)	3577.93	3035.99	2548.66	2880.37
Acidification (kg SO_2 eq)	8.37	7.05	5.86	6.85

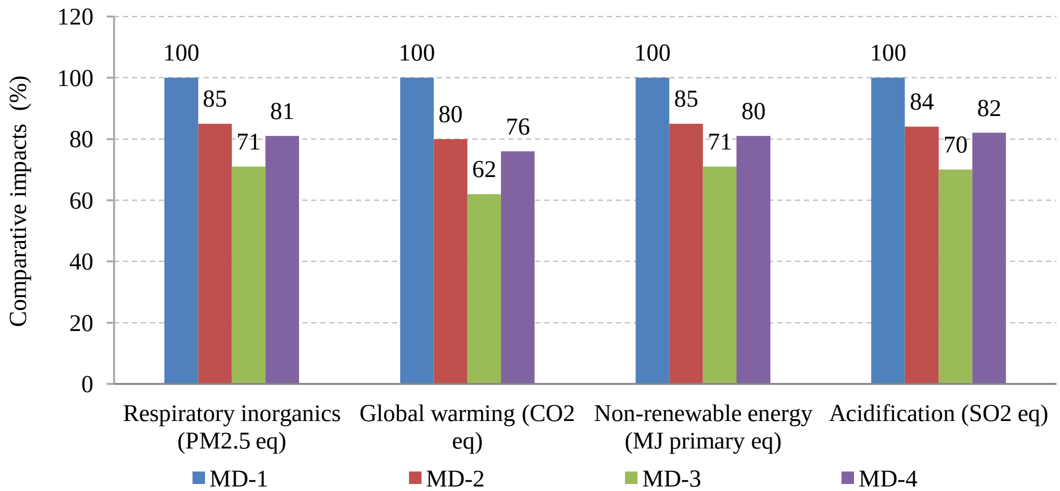


Figure 7-5 - Comparison of environmental impacts for different types of concrete using system expansion approach

7.6 Discussion

The distribution of environmental impacts is one of the unresolved issues in LCA, and the use of different allocation approaches significantly influence the outcomes of a study and subsequent decision making (Finnveden et al. 2009; Reap et al. 2008; Sayagh et al. 2010). As handling of waste materials in LCA is a methodological challenge due to their multi-functional processes, certain methodological rigor is therefore necessary.

It is obvious that allocation by mass resulted in much higher environmental impacts than those based on the allocation by economic approach. However, even using the economic allocation approach, most of the impacts for FA and SF are still higher than that of cement (Figure 7-4). The results of this study on SCMs are consistent with other studies (e.g. Habert et al. 2011; Chen et al. 2010b; Van den Heede and De Belie 2012). In addition, the economic allocation coefficients vary temporally and spatially. An example of GHGs emissions for per kg SCMs production for mass and economic allocation is shown in Table 7-12. In addition to the allocation coefficient, the final results are also influenced by the upstream and downstream data, database used, as well as system boundaries. The results show the mass allocation provides more consistent results (especially for GBFS and FA) as the ratio of mass between the main products and the by-products are relatively constant over time and regions.

Table 7-12 – GHGs emissions (kg CO_2 eq) for 1 kg SCMs for different allocations

Study	**System boundary**	**Economic allocation**			**Mass allocation**		
		FA	GBFS	SF	FA	GBFS	SF
Chen et al. 2010b	Cradle-to-gate	3.50×10^{-1}	1.49×10^{-1}	--	4.18	1.39	--
Habert et al. 2011	Cradle-to-gate	2.10×10^{-1}	1.67×10^{-1}	1.20	2.51	1.25	4.12
This study	Cradle-to-site	5.40×10^{-1}	3.50×10^{-1}	2.05	3.04	1.75	8.71

In the system expansion approach, environmental impacts were not distributed to the main product and the by-product, but induce benefits through by-product recycling, represented by the subtraction of environmental impacts. In this approach, environmental impacts of the equivalent amount of substituted materials were subtracted from the main products (for example, the environmental impact of the clinker used in cement production substituted by the equivalent amount of GBFS was subtracted from the steel-making process) (Saade et al. 2015). Thus SCMs does not convey any environmental impacts from their main products to concrete, except those related to secondary process and transport based on the design of the system expansion approach (Figure 7-2). Therefore, significant lower impacts are associated with concrete made with SCMs when the system expansion approach is adopted. An example of total GHGs emission for concrete production with SCMs for economic and system expansion approach is shown in Figure 7-6. It can be seen that about 10%, 28% and 13% lower GHGs emission is associated with MD-2, MD-3 and MD-4, respectively for the system expansion approach than the economic allocation approach. For MD-1, GHGs emission is the same for both approaches as no SCMs are used. For economic allocation, the impacts are significantly higher due to the impacts of the main products was assigned to the by-products based on economic allocation coefficient. It has already been mentioned that economic allocation coefficient is highly fluctuated, and thus the environmental impacts are also varied significantly.

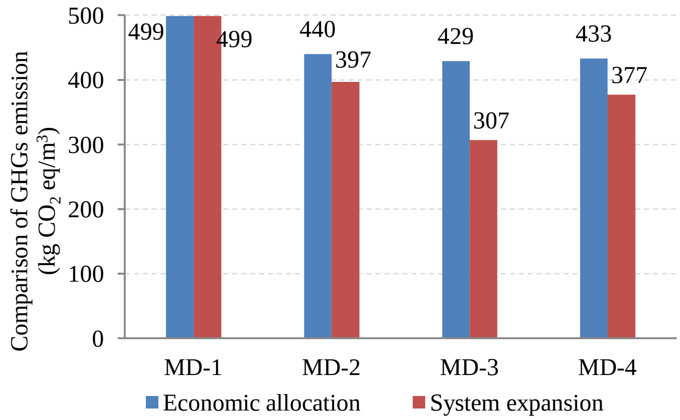


Figure 7-6 - Comparison of GHGs emission for economic and system expansion approach

As no specific allocation method is consensually agreed by researchers, the system expansion approach may be the preferable option for SCMs. Moreover, the key conceptual limitation of both the mass and economic allocation is their failure to capture the recycling benefits (Saade et al. 2015). However, Chen et al. (2010b) concluded that allocations were still preferable method as a global coherency between LCA studies was lacking in system expansion approach. This is because the choice of system boundaries, considerations and results may vary in different LCA studies due to the lack of specific guidelines for the system expansion approach.

As each environmental impacts distribution approach presents its potential advantages and disadvantages, no approach can be considered as superior over others (Saade et al. 2015). Based on the existing literature and the results of this study, a decision matrix is presented for selecting the appropriate impacts distribution approach when SCMs are used in the cement and concrete industry (Table 7-13). System expansion can be used as the preferred approach for the assessment of concrete, as this approach is able to take to account of the mass balance (between the systems), their current status of the by-products (e.g how the environmental impacts are distributed based the system expansion principles), recycling benefits (as described above), and preservation of natural resources.

Table 7-13 - Decision matrix for approach selection of environmental assessment of concrete using SCMs

Criteria	Mass allocation	Economic allocation	System expansion	Reference
Mass balance	Ensured	Varied	Ensured	Weidema 2001, 2010
By-product status	Ensured	Ensured	Ensured	EU Directive 2008
Environmental load distribution	Main product to by-product	Main product to by-product	Does not convey load to by-product	Saade et al. 2015
Recycling benefits	Failed	Varied	Ensured	This study; Crossin 2015
Way of assessment	Straightforward	Sensible based on market	Complex	Crossin 2015
Primary materials scarcity	Disregarded	Disregarded	Esteemed	Saade et al. 2015
Coherency of various LCA study	Ensured	Varied	Varied	This study; Chen et al. 2010b
Environmental impacts	Very high	High	Low	This study; Crossin 2015
Variability/ sensitivity	Very low	Very high	Low	This study
Supply and demand	Not applicable	High dependency	High dependency	Crossin 2015
Industry/practitioner acceptability	Very low	Low	High	This study
ISO preference	Second	Third	First	ISO 2006b

7.7 Summary

The distribution of environmental impacts of SCMs in concrete/concrete products and the choice of different approaches in life cycle assessment have been extensively reviewed in this paper, and a case study was conducted to support the decision making process. Based on the findings and analyses of the study, the following conclusions can be drawn:

(i) About 76% of the reviewed studies considered SCMs as wastes, although the status of SCMs has been shifted to by-products.

(ii) About 45% of the reviewed studies have used economic allocation as the allocation approach. However, economic allocation coefficients significantly varied temporarily and spatially.

(iii) Mass allocation was disregarded in most of the reviewed studies, as very high environmental impacts were associated with this approach.

(iv) According to concrete mix-designs used in this study, about 15-29%, 20-38%, 15-29% and 16-30% reduction of respiratory effect, global warming potential, non-renewable energy consumption and acidification potential, respectively were found for using SCMs than the OPC concrete through the system expansion approach.

(v) When compared with economic allocation, the use of the system expansion approach resulted in about 10%, 28% and 13% reduction in GHGs emission for MD-2, MD-3 and MD-4 concrete production, respectively.

Based on the decision matrix presented in this study, the system expansion may be the preferred approach over allocations for assessing environmental impacts of cement, concrete and concrete products. Further research on SCMs could be conducted based on the supply and demand constraints using the system expansion approach.

CHAPTER 8

DEVELOPMENT OF SOCIAL SUSTAINABILITY ASSESSMENT METHOD AND CASE STUDY ON CONSTRUCTION MATERIALS

8.1 Introduction

8.1.1 Background

Sustainability assessment of products/processes based on the life cycle assessment technique generally would consider three dimensions *viz.* environmental, social and economic. Environmental impacts in the life cycle assessment (LCA) which is intended to assess the environmental impacts throughout a product's life cycle has already been developed and reached to its standardized form in terms of methodology, evaluation and implementation (ISO 2006a). Economic perspectives for assessing life cycle costing have also found its standardized form in terms of methodology (Hunkeler 2006; Swarr et al. 2011), but the tools for social sustainability assessment of products throughout the life cycle (namely S-LCA) is still under developing.

A S-LCA approach can be used to identify, communicate and report the social impacts, sustainability knowledge, and social conditions of a product (Benoit et al. 2010; Petersen 2013). With appropriate consideration of choice, acceptance and demand, S-LCA can indirectly influence the production level of a product. For S-LCA, the collection of valid data is always a challenging issue (Kruse et al. 2009) and it can restrict the implementation of results (Traverso et al. 2013). In addition, sustainability assessment results are too complex and difficult to understand for the decision-makers (Traverso et al. 2013). Moreover, the changes of social conditions (data) occur faster than the environmental data which usually makes the study more complex (Wu et al. 2014b).

S-LCA is defined as "*a social impact (and potential impacts) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal*" (UNEP/SETAC 2009). In S-LCA, impacts regarding social and socioeconomic aspects that may affect stakeholders positively or negatively during the life cycle of a product are assessed. Jørgensen et al. (2008) proposed four impact categories of S-LCA, i.e. human rights, labor practice and decent work conditions, society, and product responsibility. UNEP/SETAC (2009) defines five stakeholder categories (including workers/employees, local community, society, consumers, and value chain actors) with six impact categories (including human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions) related to social issues of interest to stakeholders and decision makers. Social impacts are consequences of positive or negative pressures on social endpoints (Arcese et al. 2013; Macombe et al. 2011). In order to support further impact assessment and interpretation, the impact subcategories are classified within a stakeholder category, and assessed using inventory indicators. For example, the stakeholder category of worker encompasses impact subcategories of working hours, fair salary, child labor, health and safety, etc., while the stakeholder category of society includes subcategories of technology development, contribution to economic development, public commitment to sustainability issues, etc. (Lehmann et al. 2013). Several research studies have been conducted to describe various sets of S-LCA inventory indicators (Nazarkina and Le Bocq 2006; Labuschagne and Brent 2006). The inventory indicators as proposed in these studies provide measurable assessment on a specific impact of the corresponding sub-categories. For instance, the creation of permanent positions is an indicator to reflect the social impact to local community, while working hours is an indicator under the stakeholder of workers.

Some of the past S-LCA studies, including their methodologies and sub-categories are listed in Table 8-1. The choice of categories is based on the recommendations of various standards and literatures (Table 8-2). The selection of the categories, sub-categories, inventory indicators, and the model development are described in section 8.3.

Table 8-1 – Examples of some proposed S-LCA approaches and sub-categories

Author(s)	UNEP/ SETAC 2009	Jørgensen et al. 2010	Ciroth and Franze 2011	Benoît-Norris et al. 2012	Arcese et al. 2013	Ekener-Petersen and Moberg 2013	Valdivia et al. 2013	Hosseinijou et al. 2014	Henke and Theuvsen 2014	De Luca et al. 2015	Dong and Ng 2015	This study
Studied case	General S-LCA method	Validity in S-LCA	Laptop computer	Supply chain of products	Tourism	Laptop computer	Not specified	Steel and cement	Bio-energy value chains	Citrus farming	Building construction project	Construction materials
Methodology	S-LCA guidelines	Proposed validation method	UNEP/SETAC proposed methodology	The Social Hotspots Database	Social accounting and business management tools	Guidelines given by Benoît-Norris et al. 2011 using country level data	Life cycle sustainability assessment	UNEP/SETAC guidelines	7-point Likert scales on different social indicators	Multi-criteria Decision Analysis	Social-impact Model based on the UNEP/SETAC guidelines	UNEP/SETAC guidelines; GRI; Proposed sustainability index and SSG-Model
Number of category	5		5	5	3	5	2	5	3	3	3	6
Sub-categories												
Freedom of association and collective Bargaining	√		√	√		√		√			√	
Child labor	√	√	√	√		√	√	√			√	√
Fair salary	√		√	√	√	√		√	√		√	√
Working hours	√		√	√	√	√					√	√
Forced labor	√		√	√		√		√			√	√
Equal opportunities/discrimination	√		√	√		√	√	√	√	√	√	√
Health & safety (worker)	√		√	√	√	√	√	√		√	√	√
Social benefits/social security	√		√		√	√			√			√
Health & safety	√		√			√		√				√
Feedback mechanism	√		√		√	√						
Consumer privacy	√		√		√	√						
Transparency	√		√		√	√						
End of life responsibility	√		√			√						√
Access to material resources	√		√		√	√		√			√	√
Access to immaterial resources	√		√		√	√				√		√
Delocalization & migration	√		√		√	√						
Cultural Heritage	√		√		√	√		√			√	
Safe & healthy living conditions	√		√		√	√		√			√	√
Respect of indigenous rights	√		√	√	√	√						
Community engagement	√		√		√	√					√	√
Local employment	√		√		√	√		√			√	√
Secure living conditions	√		√		√	√						√
Public commitments to sustainability issues	√		√			√					√	√
Contribution to economic development	√		√			√		√	√	√		√
Prevention & mitigation of armed conflicts	√		√	√		√			√			
Technology development	√		√			√		√				√
Corruption	√		√			√	√					
Fair competition	√		√			√		√	√			√
Promoting social responsibility	√		√			√						√
Supplier relationships	√		√			√		√				√
Respect of intellectual property rights	√		√			√						√
Use stage responsibility [1,*]												√
Product service & labeling [1,*]												√
User satisfaction [1,*]												√
Training & education [1,*]												√

Public opinion on materials [2,*]			√
Support from the Government [2,*]			√
Materials (use and practice) [1,3,*]	√	√	√
Energy and water consumption (reduction strategies) [1,2,*]			√
Emissions (reduction strategies) [1,2,*]			√
Solid waste and effluent (strategies for management) [1,2,*]			√
Biodiversity (effects on local biodiversity) [1,3,4,*]			√

[1,] GRI, 2013; [2,] BECL, 2013; [3,] De Luca et al. 2015; [4,] Henke and Theuvsen, 2014; *, developed in this study based on the mentioned references

Table 8-2 - List of categories proposed for conducting S-LCA

Category	References
Consumer	UNEP/SETAC 2009
Workers	UNEP/SETAC 2009
Local community	UNEP/SETAC 2009
Society	UNEP/SETAC 2009
Value chain actors	UNEP/SETAC 2009
Labor rights and decent work	Benoît-Norris et al. 2012
Governance	Benoît-Norris et al. 2012
Human rights	Benoît-Norris et al. 2012
Community infrastructure	Benoît-Norris et al. 2012
Producer (or user)	ISO 2010; GRI 2013; This study
Socio-environment	Henke and Theuvsen 2014; De Luca et al. 2015; This study

8.1.2 Past S-LCA studies and their objectives

As a promising tool, S-LCA has undergone rapid development in terms of methodology development/improvement and case studies. However, several issues, such as selection of social indicators, analysis of results in terms of functional unit and system boundary, impact assessment, results interpretation, and difficulties in data collection (also data availability), are the main challenges for developing and conducting S-LCA (Finkbeiner et al. 2010). Social impacts can be quantified using different indicators across the entire life cycle of products. However, different from environmental LCA, quantification of impacts in S-LCA is a thorny issue. Some of the impacts can be quantified directly but others are difficult to assess, consequently, meaningful conclusions are hardly to be drawn (Hauschild et al. 2008). This is also reflected by the difficulties in selection of indicators and conversion of collected data according to function unit (Jørgensen et al. 2008, Kloepffer 2008). In addition, the scientific approach regarding the compilation of social cause-effect-chain is still lacking in S-LCA study (Ciroth and Franze 2011). In terms of the social life cycle impact assessment method, characterization and weighting of indicators are challenging topics (Hosseinijou et al. 2014). Nevertheless, methodological framework provided for systematically conducting social assessment of products along their life cycle is still at an early stage of development (Haaster et al. 2016). Therefore, more fundamental scientific effort is highly demanded.

Traverso et al. (2013) proposed a dashboard containing graphical representation of the life cycle sustainability results. Ekener-Petersen and Moberg (2013) conducted a S-LCA study on laptop computers and found some major challenging issues, including result representation, identification of relevant indicators, data availability, impact categories and functional variables. Arcese et al. (2013) developed a management tool for the tourism sector based on UNEP/SETAC guidelines and evaluated the negative and positive social impacts. According to Valdivia et al. (2013), data production and their acquisition is a key issue of a S-LCA study. The study concluded that the guidelines provided by UNEP/SETAC (UNEP/SETAC 2011) could help relieving the overall development efforts in performing S-LCA. Martínez-Blanco et al. (2014) conducted a case study on the application of S-LCA methodology on two mineral fertilizers and an industrial compost in line with the UNEP/SETAC S-LCA guidelines and the social hotspots database was adopted for the secondary processes. However, the study summarized the results based on the sub-category level, but conclusions based on the social performance were not provided. Manik et al. (2013) investigated the social implications of biodiesel production from palm oil by adopting the UNEP/SETAC S-LCA methodological guidelines. However, the study mainly focused on the upstream processes, while further study was recommended to cover the downstream level (e.g. consumers, value chain actors). Dong and Ng (2015) conducted S-LCA on building construction processes using both national level and project specific data. Hosseinijou et al. (2014) used project data for conducting S-LCA for cement and steel. All in all, S-LCA is a rapid developing methodology for assessing social impacts, especially the assessment of the social impacts of recycled construction materials/products, is still unexplored.

However, for the assessment of sustainability of recycled construction materials, the lack of several critical steps, for instance, the selection of different stakeholders, subcategories, indicators, and weighting methods, is still a major concern. This is mainly due to the necessities of the involvement of diverse types of stakeholders during the recycling of construction materials in the S-LCA study.

To overcome the aforementioned shortcomings, this study aimed to propose a comprehensive S-LCA methodological framework and provide guidelines for assessing sustainability performance for recycled construction materials. Therefore, the goal of this study is to assess the social implications and sustainability of construction materials, more specifically recycled materials by developing a comparative rating model, namely the 'Social Sustainability Grading Model (SSG-Model)'. In the SSG-Model, the following tasks are carried out: (i) to integrate a set of new impact subcategories, (ii) to introduce systematic data collection procedures and prioritization, (iii) to develop scoring scale of indicators and calculation methods/equations of impacts, (iv) to propose social sustainable index for product socio-labeling, and (v) to conduct comparative analysis and decision making for increasing the reliability and transparency of the assessment. In this research, a case study is conducted to adopt the proposed SSG-Model for the assessment of specific recycled materials in Hong Kong. This work can contribute to the detection of the hotspots in social sustainability aspects associated with recycled materials, which is very useful for strategic design for sustainability issues.

8.2 Research design

This study is consisted of several individual stages. The first stage is the development of a S-LCA method for quantitative evaluation of the comparative social sustainability for recycled materials. In this stage, a four-phase structure is used for method development. The first phase relates to the setting of goal and scope definition of the relevant category and sub-category and the selection the indicators. The second phase is inventory analysis and mainly focuses on data collection. Life cycle sustainability assessment and comparative sustainability interpretation (the 3^{rd} and 4^{th} phases) are then conducted. The overall research design of this study is shown in Figure 8-1, which is developed based on the established guidelines for social life cycle assessment (UNEP/SETAC 2009-11) and LCA for ISO standards (ISO 2006a,b). The detailed procedures for identifying category and sub-category, selecting indicators, data collection and benchmarking the indicator values are provided in section 8.3.

The second stage of the study is to conduct a S-LCA case study of recycled construction materials. The performance of recycled construction materials are compared with the conventional natural materials. This comparative case study has been conducted by using real data from the respective manufacturers (details have been provided in section 8.4).

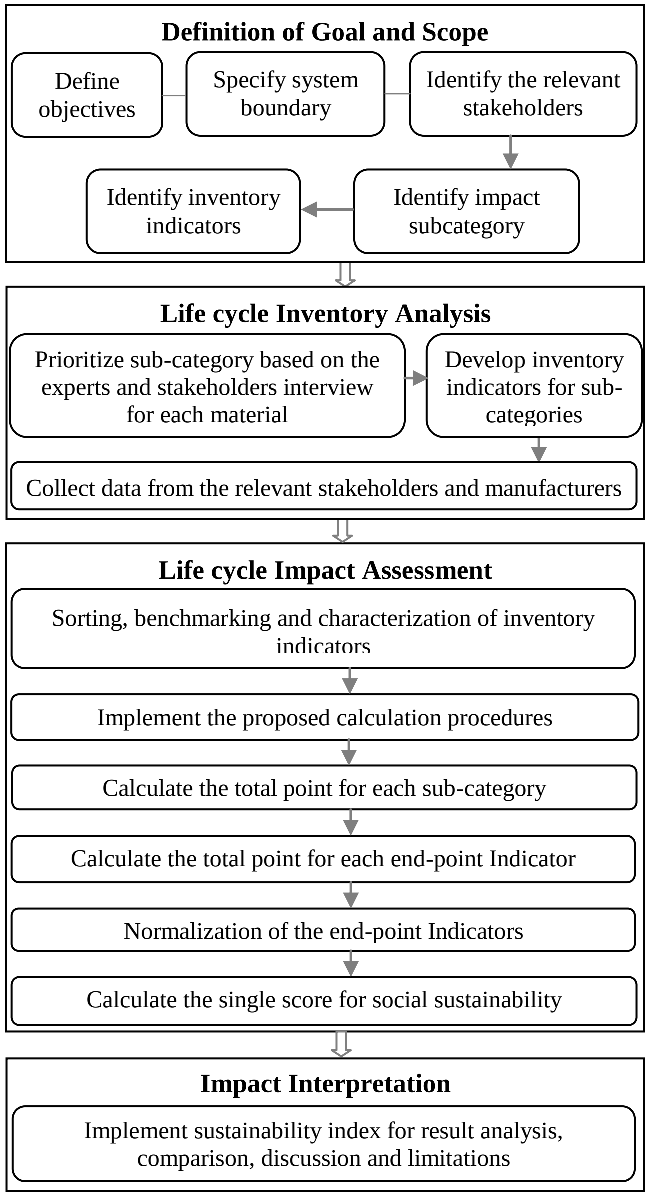


Figure 8-1 - Schematic illustration of the proposed S-LCA design

8.3 Development of SSG-Model

The social sustainability grading model (SSG-Model) is an assessment tool for evaluating social sustainability of construction materials in a quantitative and comparative way. The SSG-Model was proposed based on the UNEP/SETAC guidelines and spreadsheet, the indicators and sustainability reporting guidelines provided by the Global Reporting Initiatives (GRI), and the indicators provided by Hong Kong Business Environment Council Limited (BECL) for construction sustainability (BECL 2013). A two-stage research approach was used in this study; the first one is a qualitative research based on the expert interviews to identify, select and prioritize the relevant stakeholder categories and impact sub-categories, and the second one is the operational research based on a case-specific survey to collect the required data to obtain the objectives. The main features of the model include:

(i) Methodology based on ISO standards series (ISO 14040/14044) for LCA, and ISO 26000 for social responsibility (ISO 2010) and GRI (2013),

(ii) Stakeholder categories and impact sub-categories complying with UNEP/SETAC (2009) for S-LCA guidelines, GRI guidelines for sustainability reporting of products, and BECL guidelines,

(iii) The model contains predefined inventory indicator (compiled from UNEP/SETAC methodological sheets and GRI guidelines) and variables towards social sustainability assessment of a product,

(iv) All types of data (e.g. qualitative, quantitative and semi-quantitative) are applicable in this model, and the model provides guidelines for systemic data collection procedures,

(v) Indicator benchmarking based on national or international guidelines, and

(vi) Simple calculation and grading systems for result interpretations.

8.3.1 Goal and scope definition

The goal and scope definition phase defines the overall objectives, system boundaries, sources of data and the functional unit of the study (Blengini 2009). The goal of this study is to develop an effective and easy-to-handle S-LCA method to assess and/or compare the social sustainability of construction materials. Although material selection is the primary focus in this study, the proposed methodology can also be applied for comparative assessment of products, because almost all materials are the subject of transformation into products in their life cycle.

For assessing environmental impacts in the LCA, the system boundary defines the processes and life cycle stages which include the inputs and outputs of energy and materials. In a S-LCA study, the system boundary should include those that are directly influenced by the company, and the social impacts derived from the use phase of the product itself (Hosseinijou et al. 2014). However, system boundary sets the scope of how many details will be involved in a study. It may vary from study to study, and hence it should be object-oriented. Therefore, in S-LCA, the system boundary should include the social factors, such as various stakeholders (e.g. local community, manufacturer, employee, worker, supplier, distributor, consumer, recycler, waste manager, etc) associated with the materials. In this study, the system boundary is 'cradle-to-grave' of the social dimensions of the construction materials. All the relevant steps (e.g. raw materials extraction/collection, processing, transport and use, and their associated stakeholders such as producer, supplier, recycler, manager, planner, local community, etc) are included in the model during the hotspot analysis for materials/ products as shown in Figure 8-2.

In S-LCA, many of the data used are qualitative and semi-quantitative. But qualitative data is quite hard to express by functional unit (FU) (Benoit et al. 2010; Benoıt-Norris et al. 2011). According to Kruse et al. (2009), biophysical flows (e.g. raw materials, energy, waste and emissions) are more easily quantifiable and are directly linked to the FU in a LCA (for assessing environmental impact). However, the causal relationship is usually not fairly straightforward and difficult to quantify in S-LCA. Hence, the S-LCA indicators are categorized into two types: (i) additive indicators which are quantifiable and directly linked to FU, and (ii) descriptive indicators which cannot be related to the FU but can still capture the important points. To resolve the complexity in linking the social indicators to FU, a scoring approach has been used to express the social impacts. This is because the scoring system is very important for capturing both of the quantifiable and unquantifiable data (Hosseinijou et al. 2014). The adequacy of an S-LCA methodology heavily depends on how the unquantifiable data are coped with. Hence, the scoring system developed in SSG-Model will be used to translate all inventory data (both additive and descriptive) to impacts in a comprehensive way. In addition, benchmarking approach has been adopted for all data to capture the real impacts before applying in the scoring system (section 8.3.3.1). Finally, three equations have been proposed for aggregation of impacts (from indicators to sub-category level, then to end-point category level, and finally to single score) (described in section 8.3.3.2). Therefore, the proposed SSG-Model will use an effective scoring approach to express the social performance to social sustainability by adopting a proposed sustainability index.

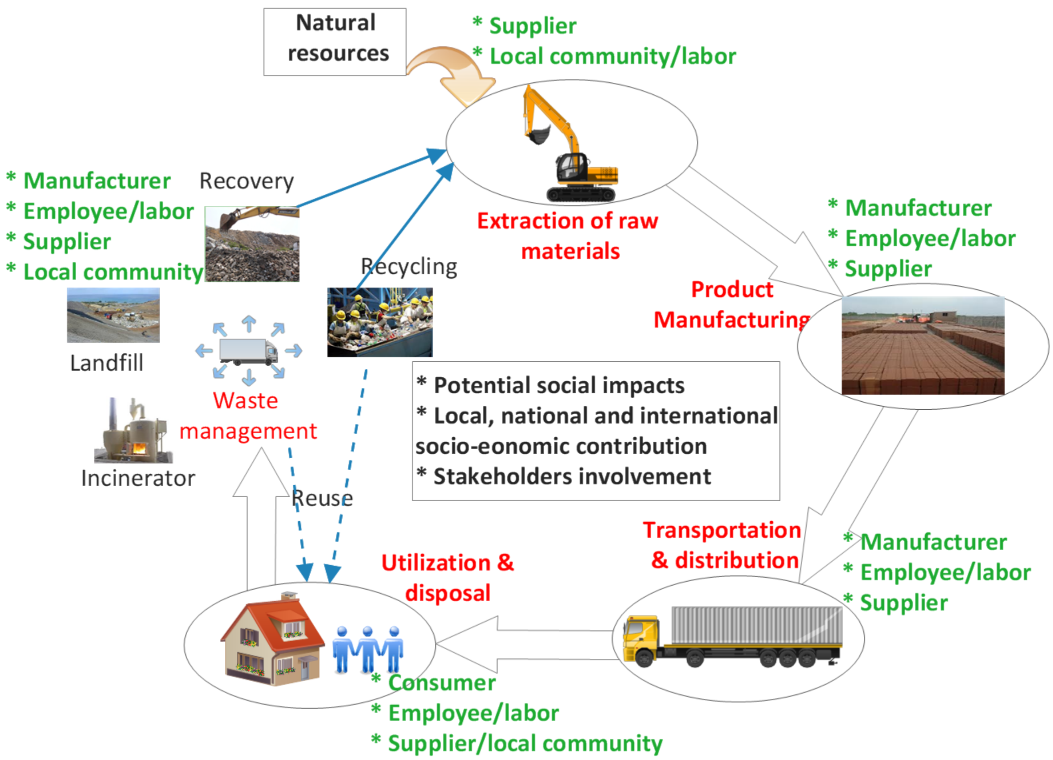


Figure 8-2 - The system boundary for SSG-Model

8.3.2 Life cycle inventory analysis

8.3.2.1 General approach

The life cycle inventory (LCI) for social indicators depends on the studied sector and the national context (Hosseinijou et al. 2014). Dreyer et al. (2006) argued that social impacts of various stakeholders of a product life cycle depend on the product chain. In LCI phase, it is important to define and select the stakeholder categories, impact sub-categories and relevant indicators of the study. A combined top-down and bottom-up approach may be useful for LCI (Kruse et al. 2009).

In addition, researchers argued that the factual implementation of the sustainability concept is one of the main challenges in the context of social dimensions; how sustainability performance can be measured for products (Finkbeiner et al. 2010; Benoit et al. 2010; Wu et al. 2014b;

Kloepffer 2008). Therefore, this study proposes a SSG-Model for comparative sustainability assessment by following the established guidelines.

The stakeholder categories are adopted based on the national and international guidelines and standards (see Tables 8-1 and 8-2). This study follows the five stakeholder categories proposed by UNEP/SETAC (2009), namely producers of the concerned materials, workers/employees, the general public (local community), government and society, and traders of the materials. Moreover, an additional category, i.e. socio-environmental performance of the material/product, is also included to consider the other relevant stakeholders, such as producers and recyclers.

Several S-LCA studies also emphasized and included the main environmental flow and their contribution to social impacts (Hosseinijou et al. 2014; Henke and Theuvsen 2014; De Luca et al. 2015). Although environmental consequences are mainly included in LCA, recycling systems also carry a significant social impact which should be included in a sustainability assessment. For example, different green building rating systems adopt different crediting systems for the use of recycled materials (and contents), waste management, emission reduction, etc. in certification (Wu et al. 2016). As the model is constructed for assessing the social sustainability for recycled materials, assessing the socio-environmental performance of the concerned materials/products is in particular important, and this has been included as a separate category in the model.

Linking subcategories of each category to end-point impact category is a challenge in S-LCA. For example, Blom and Solmar (2009) proposed to use a separate impact indicator to represent each sub-category, whereas another method linking sub-categories to the most of the impact categories was adopted by Franze and Ciroth (2011).

In addition, according to the guidelines of UNEP/SETAC (2009), GRI (2013) and BECL (2013), the possible sub-categories were screened based on the objective of the study, target materials and expert's suggestions. Subsequently 30 relevant sub-categories were selected for constructing the SSG-Model. Some of the impact categories were excluded from the model. For example, sub-category 'consumer privacy' under the category of 'producer of the material' was excluded, as this is not relevant to construction materials recycling in Hong Kong. It is also noted that some sub-categories, such as ‘child labor and equal opportunity/discrimination’ are included as indicators of sub-category ‘fair salary and employee characteristics’, and ‘secure living conditions’ is included as indicator in the sub-category of ‘safe and healthy living conditions’ in SSG-Model (see Appendix C, C1). In addition, SSG-Model can be fitted for any geographical region, and the sub-categories can be modified, included or excluded based on specific case study design. After identification of the sub-categories for each category, inventory indicators were defined and selected based on the guidelines provided by UNEP/SETAC (2010-11), GRI (2013), BECL (2013), ISO (2010) and other literatures. Finally, the sub-categories and inventory indicators were revised and then verified by the experts in the relevant field.

The proposed SSG-Model for conducting social sustainability assessment of materials/products is shown in Figure 8-3. The model consists of 6 categories, 30 sub-categories, 6 end-point categories and 1 sustainability index (also called single score).

A mid-point category shows the impact from cause-effect chain (e.g. real phenomena), while an end-point category may facilitate more structured and informed weighting, particularly across sub-categories. In addition, the end-point level is more understandable and easily comparable as the complexity of wide range of the mid-point categories is reduced. In the SSG-Model, the results can be presented in both ways (e.g. mid-point and end-point categories). The results of the mid-point and the end-point categories for the case study are described in sections 8.4.2 and 8.4.3.

8.3.2.2 Descriptions of categories and sub-categories

The first stakeholder category is the producer of the concerned materials which includes five sub-categories focusing on the producer’s responsibility on health and safety issue to the user, use stage responsibility, end-of-life responsibility, labeling of the products, and user satisfaction on the concerned materials/products.

The second category is the workers/employees of the company who produce the concerned materials/products. This category includes several sub-categories for addressing the social-economic consequences of the workers.

The third category is the general public (local community) who have concerns on the community advantages and disadvantages of the concern materials/products, such as creating employment/local employment, community engagement (e.g. recycling), access resources, health and safety of the living environment and attitude towards the concern materials/products.

The fourth category is the society and government which includes several sub-categories focusing on the commitment of the society regarding sustainability issues, economic and technology development, as well as government support towards social sustainability.

The fifth category is associated with the social consequences (e.g. fair competition, supplier relationships, intellectual property right, etc.) and corporate social responsibility of the traders/suppliers.

The sixth category is the socio-environmental performance, which includes five different sub-categories related to the environmental management systems for producing the concern materials. In the proposed SSG-Model, several sub-categories are included in this category, such as the use of recycled materials, percentage of renewable water and energy consumption, reduction rate or target for non-renewable resources and emissions, efforts paid to solid waste and effluent management, and impacts on the surrounding environment (Figure 8-3).

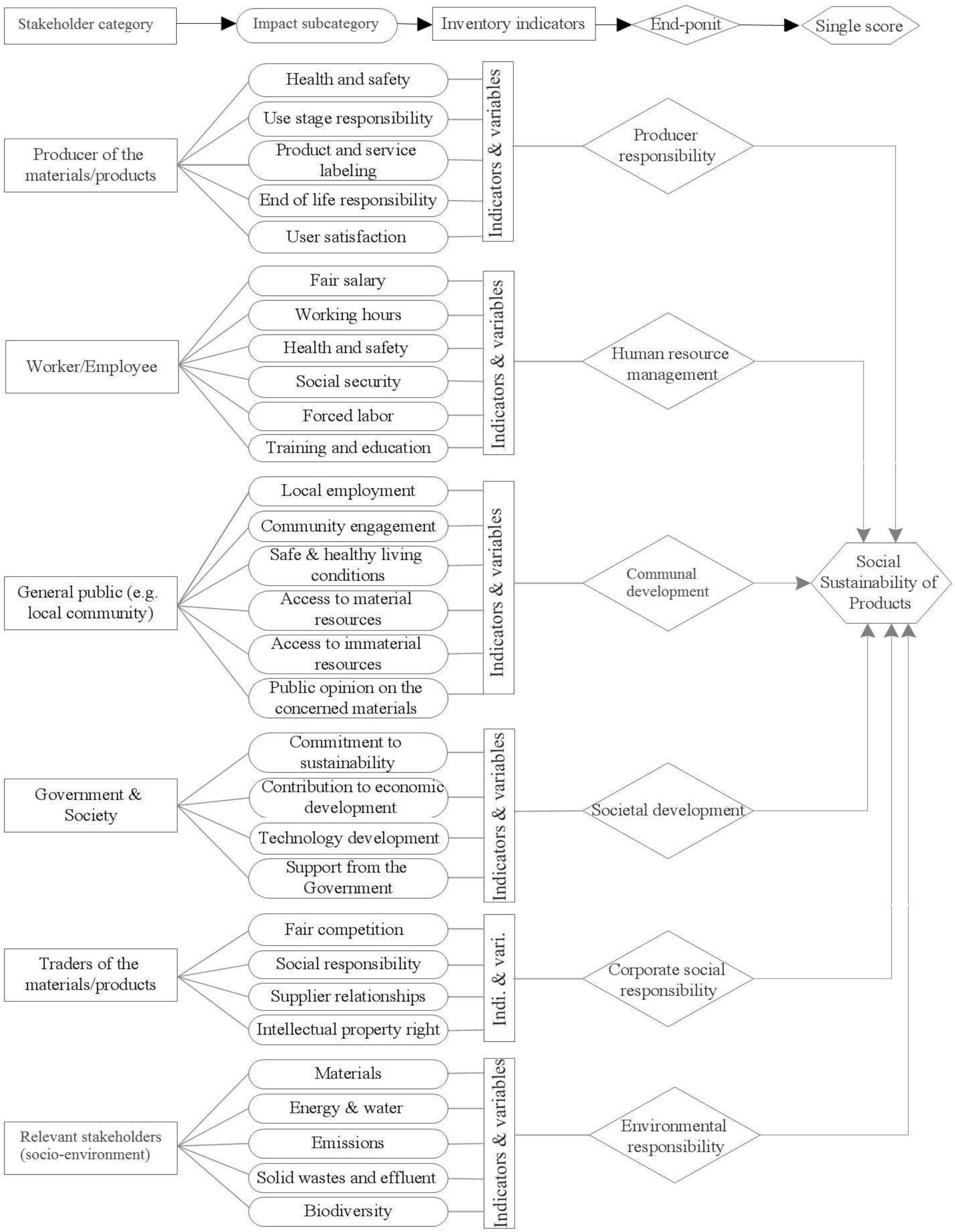


Figure 8-3 - The main categories and sub-categories of the SSG-Model

8.3.2.3 Hotspot identification

Prioritization of the sub-categories is crucial for a S-LCA study, as collecting data of such is considered complex, time consuming and sometimes irrelevant to a particular case. Hosseinijou et al. (2014) argued that hotspot analysis may be an effective way to identify the most significant social concern for a particular material or product. Benoit-Norris et al. (2011) also argued that significant and potential social impacts and also opportunities for social improvement can be highlighted by social hotspot analysis.

In S-LCA, prioritization was emphasized and suggested by several studies (e.g. Benoit-Norris et al. 2012; Garrido et al. 2016; Zanchi et al. 2016). However, till now only few studies (e.g. Hossainjou et al. 2014) have used prioritization on the sub-categories level. Therefore, the SSG-Model uses the same approach to identify the most significant, relevant and specific sub-categories. The indicators for each sub-category have been developed and then verified by the experts. The weighting factor for hotspot identification is shown in Table 8-3. After that the hotspot can be identified from the pre-defined sub-categories through the experts' interviews.

Table 8-3 - Prioritizing scale for sub-category (and indicators) based on importance

Weighting factor	Prioritize scale
1.00	Very important
0.75	Important
0.50	Neutral
0.25	Less important
0.00	Not important/irrelevant

8.3.2.4 Data collection

For S-LCA, site/case-specific first hand data is most desirable instead of national level data or using database (e.g. social hotspot database). This is because the national level data may be too broad and not applicable. In addition, the limitations for using social database have been identified by Hosseinijou et al. (2014). Therefore, it is preferable to use case–specific data for a SSG-Model, although its collection is rather complex and time consuming.

Unlike LCA (for assessing environmental impacts), S-LCA relies on different types of data including qualitative, quantitative and semi-quantitative data (Benoit-Norris et al. 2011). The data collection method is mostly interviews with the human resource department of the company, employees/workers, industry engineers, relevant researchers, community members, suppliers and consumers/users of the materials. Moreover, national and international data provided by different organizations are also needed for referencing or benchmarking the indicators. The data collection procedure for the proposed SSG-Model is given in Figure 8-4. It is important to mention that a combination of site (case) specific core data and expert interview is necessary to develop the model.

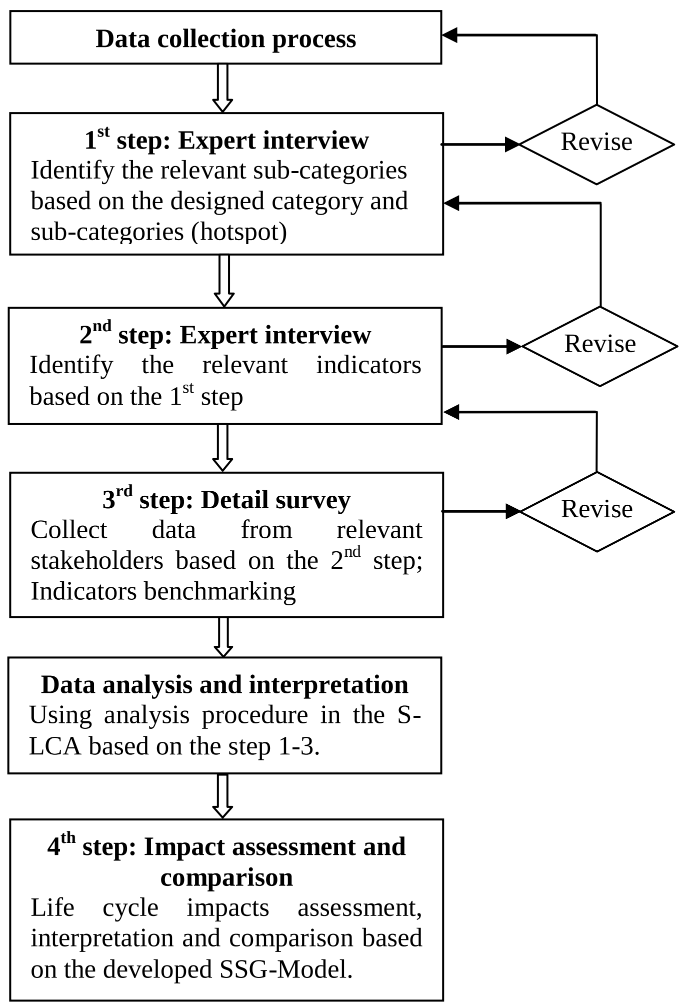


Figure 8-4 - Data collection procedure for the proposed SSG-Model

8.3.3 Life cycle impact assessment (LCIA)

8.3.3.1 Indicators benchmarking

After collecting the case-specific data, it is important to sort and arrange them based on the types of data. Benchmarking for each indicator has to be developed based on the national reference. However, international references can also be used when national data is not available. After benchmarking all data, the corresponding score needs to be given. A Likert scaling approach is proposed for scoring indicators based on their performance (shown in Table 8-4). It is noted that the possible score is '0' to '1' which indicates strongly negative (or highly unsustainable) to strongly positive (or highly sustainable).

The qualitative (range data) and quantitative data can be used directly for scoring based on the benchmarking. However, indirect scoring system is needed for the semi-quantitative data (which need to indirect weighing based on respondents' opinion as rating). In this case, the model allows the incorporation of the open ended opinions of the respondents. For example, if the answer is "Yes" or "No" for any question, then the model would ask the respondents to specify the level or extent or briefly describe the reasons. After that, based on the opinions or reasons given, the answer of the specific question can be further classified according to Table 8-4.

Table 8-4 - Indicator scoring scale of responses

Points	Category (question and answer response)
1.00	Strongly positive/ fully agreed/ very highly related/ highly compatible with national or international law
0.75	Mostly positive/ Moderately agreed/ highly related/moderately compatible
0.50	Neutrally affected/ agreed/ neutrally related/compatible
0.25	Mostly negative/ partially disagreed/ moderately negative/negatively compatible
0.00	Strongly negative/ fully disagreed/ highly unrelated/ incompatible with national or international law

8.3.3.2 Impact calculation

All the indicators will have specific points based on benchmarking for each sub-category. Benchmark can also be used as indicators characterization based on the best practice or national and international references, ranging from 0.00 to 1.00 (indicating the worst practice or highly unsustainable practice to the best practice or highly sustainable practice based on the national and international standards, using the same scoring system mentioned in Table 8-4, and an example is provided in Appendix, C2). The SSG-Model used end-point indicators which can be helpful for identifying the impact pathway and also achieving the final goal of the study. It can be seen from Figure 8-3 that the SSG-Model uses six end-point impact categories, namely i) producer responsibility, ii) human resource management, iii) communal development, iv) societal development, v) corporate social responsibility, and vi) environmental responsibility. The single score, namely 'social sustainability of product' can be an effective way to compare social sustainability of different materials/products.

To achieve the objectives, the developed model includes inventory indicators for specific categories and sub-categories. The number of inventory indicators is flexible. It is possible to modify or change the number based on specific case study design. However, it is noted that the number of indicators for each sub-category should be sufficiently large enough to achieve the objective of that sub-category**.** In this model, characterization is needed to define the indicator score based on the respondents' response and benchmarking. The normalized score of a sub-category can be calculated by using Equation 8-1. The weighting factor (co-efficient of indicator based on Table 8-3) will be determined based on the expert interviews for hotspot identification (based on the importance of each sub-category).

$$SS_a = \frac{\left[\sum_{n=i}^{I} Ii \times COI\right]}{I_n} \qquad (8\text{-}1)$$

where,
SS_a = Net score of sub-category *'a' (score should be within 0 to 1)*
I_i = Indicators *'i'(benchmarked score based on Table 8-4)*
I_n = Number of indicators of sub-category *'a'*
COI = Co-efficient of Indicator *'i' (i = 0 to 1 based on Table 8-3)*

The normalized net score for each end-point indicator can be calculated by using Equation 8-2.

$$SE_a = \frac{\sum_{n=i}^{S_c} SS_a}{\sum_{n=i}^{S_c} COI} \qquad (8\text{-}2)$$

where,
SE_a = Net score of end-point category *'a' (score should be within 0 to 1)*
S_c = Sub-category
SS_a = Sum of the total score of all sub-categories *'a'*
COI = Sum of the total co-efficient of end-point indicator *'a'*

The net score of the social sustainability (SSS) index for a product can be calculated by using Equation 8-3 (the range of SSS is 0.00 to 1.00).

$$SSS = \frac{\sum_{n=i}^{S_E} SE_a}{\sum_{n=i}^{S_E} (I_a \times W_f)} \qquad (8\text{-}3)$$

where,
SE_a = Sum of the total normalized score of all end-point indicators (n= a, b, c, ….f)
I_a = End-point indicators 'a'; S_E = End-point category
W_f = Weighting factor of end-point indicator 'a' (W_f is assumed to be 1 for all end-point indicators)

The impact calculation hierarchy is shown in Figure 8-5.

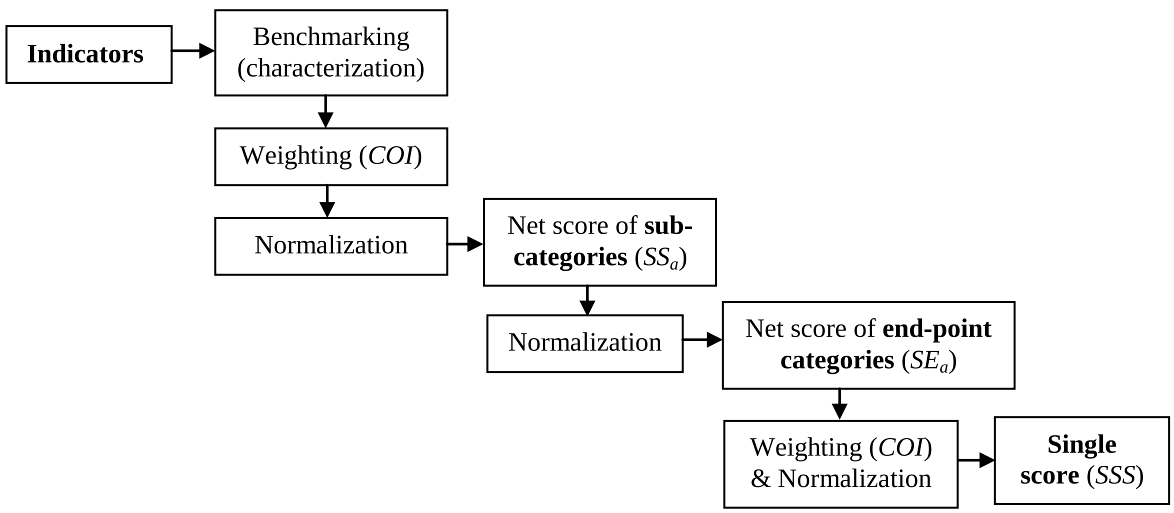


Figure 8-5 - Impact calculation hierarchy towards SSS

8.3.4 Impact interpretation

According to ISO 14040 (2006a), the results of an LCIA are summarized for decision making in accordance with the study aim as defined in the first phase. The weighted score achieved by the inventory indicators will then be normalized to get the sub-category and end-point scores by using Equations 8-1 and 8-2.

Similarly, the six end-point indicators will then be weighted (an equal weighting factor for all end-point indicators is assumed) towards the final SSS. The SSS will be between 0.00 to 1.00, indicating the range of sustainability from ‘highly unsustainable’ to ‘highly sustainable’ based on the product’s performance (meaning strongly negative/highly un-satisfied to strongly positive/satisfied) (Table 8-5). Table 8-5 indicates the SSS based on the net scores achieved from the end-point indicators, which will be then used to assess the level of sustainability based on the five grading scale (A to E), and can be used to compare different materials/products based on their social sustainability performance.

Table 8-5 - Social sustainability index based on five grading scale

Sustainability index	Grade	Level of sustainability	Significance
0.81 - 1.00	A	Highly sustainable	Strongly positive /strongly satisfied
0.61 - 0.80	B	Sustainable	Highly positive/ highly satisfied
0.41 - 0.60	C	Neutral	Moderately positive/ satisfied
0.21 - 0.40	D	Unsustainable	Negative / un-satisfied
0.00 - 0.20	E	Highly unsustainable	Strongly negative / highly un-satisfied

8.4 Case study: Comparative social sustainability performance assessment of construction materials

The aim of this case study is to assess the social sustainability of commonly used construction materials (such as aggregates). In Hong Kong, more than 90% of the natural aggregates are imported from mainland China. In addition, recycled aggregates are produced from construction and demolition (C&D) waste and also from waste glass (post consumer glass bottles) locally for lower grade concrete applications (e.g. paving blocks) (Hossain et al. 2016b,c). Recycled aggregates from C&D waste can also be used as engineering filling materials. However, the recycling rates and the use of recycled aggregates derived from the above waste materials are low.

This case study explored the relative sustainability based on social performance of natural and recycled aggregates. It is believe that the study will help to increase the understanding of social sustainability and performance of the construction industry and help to use more sustainable construction materials. In addition, the developed SSG-Model can be applied as a complimentary model to LCA (for environmental impacts) in the construction industry for promoting sustainable construction.

8.4.1 Inventory analysis

The necessary information for this case was collected from the respective manufacturers, suppliers and associated stakeholders. It is already been mentioned that a twofold research approach is used in this study; (i) the qualitative research based on the expert interviews to prioritize the important stakeholders, categories, sub-categories and inventory indicators, and (ii) the operational research based on the field survey to collect the required case-specific data. The research design for this case study followed the method outlined in Figure 8-1, and the data collected procedure followed those in Figure 8-4. The inventory analysis followed the SSG-Model described in section 8.3.2. To implement the SSG-Model for construction materials, an expert and stakeholders survey was conducted to identify the 'hotspot' (selecting sub-categories based on the relevance and importance designed in Figure 8-3). More than 100 stakeholders were invited to participate in this online survey through Google forms (see Appendix, C4). Simple random sampling method was used to select the relevant stakeholders in this study to identify the hotspot. Stakeholders were asked to identify and select the relevant sub-categories based on the prioritization scale mentioned in Table 8-3. A diverse group of stakeholders participated in this evaluation, viz. academics, producers, recyclers, users and traders of the materials, the general public and government officials. About 40 full responses were received (response rate was about 38%). The background of the participants for the hotspot identification is given in Figure 8-6.

In the third stage of data collection based on Figure 8-4 (site specific core data), the inventory data for producing recycled aggregates (for both waste glass and C&D waste) were collected from the suppliers, managers and workers from the leading recycled aggregate producers in Hong Kong as the first hand data through on-site structured questionnaire survey. In addition, the required data for natural aggregates (for both crushed stone and river sand) production and transportation were collected from the importers, suppliers and producers using the same questionnaire. The information regarding the manufacturers is hidden due to the confidentiality.

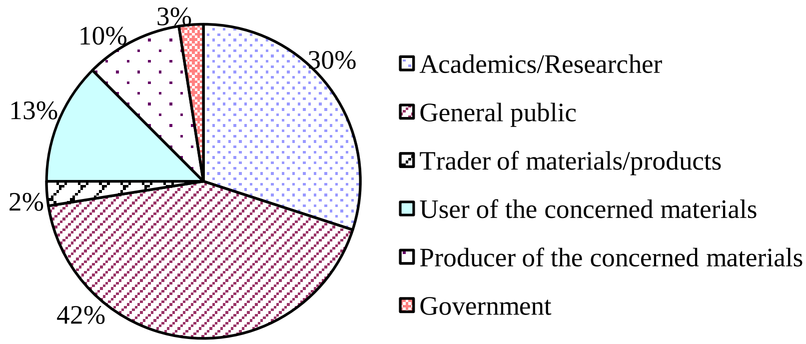


Figure 8-6 - Experts and stakeholders questionnaire survey for hotspot identification

8.4.2 Impact assessment

All the questionnaires for hotspot identification were analyzed and scores were given based on the responses from the experts and stakeholders. An interval scaling approach was applied in the average score for each sub-category where the highest value was 0.905 and the lowest value was 0.474. Based on the approach, the mid-point was calculated and then ranked according to the average score of each sub-category (Table 8-6).

Table 8-6 - Interval scaling approach for prioritizing sub-categories

Rank	Scale	Mid-point
1st	0.905	
2nd	0.797	0.851
3rd	0.689	0.743
4th	0.581	0.635
5th	0.474	0.528

The results for prioritization of the sub-categories (hotspot) are given in Figure 8-7. The survey results indicated that four sub-categories were identified as the most important sub-categories for the construction materials among the sub-categories mentioned in the SSG-Model structure (Figure 8-3). These are: ensuring the health and safety of the products by the producers, the health and safety of the workers of the relevant industries, the company's commitment to sustainability, and the energy and water consumption in the category of socio-environmental performance. In addition, nine indicators were identified as important sub-categories, ten indicators were identified as neutrally important, five indicators were identified as less important, and two were identified as not important. The sub-categories that were rated as not important/irrelevant were excluded from further analysis.

Concerned Sector	Sub-categories	Prioritization
Producers of the concerned materials/products	Health and safety	Very important
	Use stage responsibility	Neutral
	Product and service labeling	Neutral
	End of life responsibility	Neutral
	User satisfaction (based on quality)	Important
Worker/Employee of the relevant industry	Fair salary	Important
	Working hours	Important
	Health and safety	Very important
	Social security	Neutral
	Forced labor	Neutral
	Training and education	Neutral
General public (e.g. local community)	Local employment	Less important
	Community engagement	Less important
	Safe & healthy living conditions	Important
	Access to materials resources	Not important
	Access to immaterial resources	Not important
	Public opinion on the concerned materials	Neutral
Government (e.g. contribution to Hong Kong and support from the Government)	Commitment to sustainability	Very important
	Contribution to economic development	Important
	Technology development	Neutral
	Support from the Government	Important
Traders of the materials/products	Fair competition	Neutral
	Social responsibility	Less important
	Supplier relationships	Less important
	Intellectual property right	Neutral
All stakeholders (Socio-environmental performance of the concerned materials/products)	Materials (use of natural & recycled materials)	Important
	Energy & water consumption	Very important
	Emissions to air, water and soil	Important
	Solid wastes and effluent treatment	Important
	Biodiversity (effects on local biodiversity)	Less important

Very important	Important	Neutral	Less important	Not important

Figure 8-7 - Social hotspot identification of the concern materials/products

Detailed inventory data were collected from the respective stakeholders based on the data collection procedures given in Figure 8-4. Data of some indicators were additive and collected as per FU, but most of them were descriptive. Therefore, to reduce the complexity for FU in S-LCA, the rating approach was applied in this case (described in section 8.3 at SSG-Model development). Some inventory data could not be found, and some were not applicable for certain stage or material. In this case study, country level average data were used for the missing data.

The collected data were then screened, benchmarked and used for interpretation. The data were then fitted in the benchmarking worksheets to assess the relative magnitudes for each indicator using the predefined scale (Table 8-4). For this case study, totally one hundred and nine indicators were used within the twenty eight sub-categories under six categories (further details can be found in Appendix C, C1). An Excel worksheet was developed by incorporating all the categories, sub-categories and indicators. The calculation equations (described in section 8.3.3.2) were integrated in this worksheet to calculate the impacts. Finally, the score of each indicator after benchmarking was input into the worksheet. The snapshot of calculation worksheet is given in Figure 8-8. It can be seen that the score of each indicator is input in one column (named indicators' score), and the weighting factor is used in the next column. The weighted score for each indicator is found at the next column, and the normalized score for each sub-category is found next to the weighted score of the indicators. The normalized score for each end-point category is found at the last column. Finally, the SSS is obtained from the weighting of the normalized scores of all end-point indicators (using Equation 9-3). However, some of the indicators are left blank and are not included in the calculation, as data for those indicators were not provided by the respondents. For example, the producer of recycled aggregate did not receive any noticeable compliant from the users related to its safety issues (Figure 8-8). The example of indicator benchmarking and calculation is given in Appendix C (C2 and C3).

		Indicators' score	Weighting factor	Weighted score of indicator	Sub-category score (normalized)	End-point score (normalized)
1	Social sustainability assessment; a comparative case study on construction materials (recycled aggregates,C&DW)					
2						
3		Indicators' score	Weighting factor	Weighted score of indicator	Sub-category score (normalized)	End-point score (normalized)
4	Category 1: Producer and user of the concerned materials/produ					
5	***1.1. Sub-categories: Health and safety***					
6	1. Level of potential safety with the product for transport and handling?	0.5	1	0.5		
7	2. Is the product harmful from a health perspective through its lifecycle?	1	1	1		
8	3. Is there any safety information or sign of the products?	0	1	0		
9	4. Is there any consumer complaint about health and safety issues?		1	0	0.5625	
10	5. Total number of user complaints per year about health and safety issues.		1	0		
11	6. Is there any quality of labels of health and safety requirements?		1	0		
12	7. Is there any a potential emission or leakage or discharge during utilization of the proc	0.75	1	0.75		
13	8. Is there any potential measure to prevent it?		1	0		
14	***1.2. Sub-categories: Use stage responsibility***					
15	1. Is there any policy available for use stage responsibility by the relevant materials proc	0.5	0.5	0.25	0.3125	
16	2. Any future risk of accident/health damage for the final user imposed by the materials'	0.75	0.5	0.375		
17	***1.3. Sub-categories: Product and service labeling***					0.653846154
18	1. Is the product suitably labeled with regards to it component parts or ingredients?		0.5	0		
19	2. Compliance with international accounting practices and regulatory requirements (tran	1	0.5	0.5	0.458333333	
20	3. Certification standards, labels, and special indices that may be used to provide inforn	0.75	0.5	0.375		
21	4. Is there any publication of a sustainability report about social and environmental life c	1	0.5	0.5		
22	5. Certification/label the organization obtained for the product, or company sustainability rating (e.g. Dow Jc		0.5	0		
23	***1.4. Sub-categories: End-of-life Responsibility***					
24	1. Are there any management efforts to address end-of-life service of the products such	1	0.5	0.5	0.416666667	
25	2. Level of management attention to end-of-life impacts of the products.	0.5	0.5	0.25		
26	3. Do producers have any buy back and recycle or safely dispose of wastes scheme?	1	0.5	0.5		
27	***1.5. Sub-categories: User satisfaction (based on quality)***					
28	1. Do the materials/products maintain international/national standards on the quality?	1	0.75	0.75		
29	2. What is the level of standards of the concerned materials/product?	0.5	0.75	0.375	0.375	
30	3. Is there any practice related to user satisfaction (surveys measuring customer satisfact	0	0.75	0		
31	4. Level of user satisfaction on the materials/products	0.5	0.75	0.375		
32						
33	Category 2: Worker/employee					
34	***2.1. Sub-categories: Fair salary and employee characteristics***					

Figure 8-8 - Screenshot of the calculation worksheet

The aggregated results from the different life cycle stages can be presented by different ways. For example, the result can be divided according to the sub-categories in order to display how the products affect the different sub-categories in their life cycle associated with different processes (Hosseinijou et al. 2014). In addition, the impacts can be aggregated and displayed according to the different operational stages in order to show the magnitude of the impacts in different life cycle stages (Figures 8-9 and 8-10).

Using the similar calculation worksheets (mentioned in Figure 8-8), the weighted score of all indicators, and normalized score of all sub-categories and end-point categories were calculated. The normalized scores of the sub-categories for the natural and recycled aggregates are presented in Figure 8-9. The normalized score of the sub-category ‘health and safety’ for recycled aggregates from C&D waste under the category of ‘producer and users of the concerned materials’ is 0.56, which is lower than that of the natural aggregates (0.63) derived from crushed stone, river sand (0.69) and recycled aggregates from waste glass (0.63). According to the sustainability scale used in the SSG-Model, recycled aggregates from C&D waste has higher potential health impacts and safety issues during demolition, sorting, transport and processing, compared to others. In addition, some potential health issues are associated with the use of C&D waste due to the potential leaching of contaminants. However, the score of 'materials' under the category of 'socio-environmental performance' for recycled aggregates derived from C&D waste and waste glass is 0.75. This is because the materials are entirely produced from waste materials, which help to clean up the environment and reduce the associated environmental and social impacts due to landfill disposal. In contrast, natural aggregates are produced from natural resources, which is responsible for natural resource depletion and also have negative social impacts. Therefore, their scores in this sub-category is zero, as they negatively affected the social environment.

Category	**Sub-categories**	**Normalized score**			
		CS	RS	C&DW	WG
Producers of the concerned materials/products	Health and safety	0.63	0.69	0.56	0.63
	Use stage responsibility	0.25	0.25	0.31	0.38
	Product and service labeling	0.33	0.33	0.46	0.46
	End of life responsibility	0.00	0.00	0.42	0.38
	User satisfaction (based on quality)	0.70	0.70	0.38	0.38
Worker/employee of the relevant industry	Fair salary	0.66	0.66	0.75	0.75
	Working hours	0.38	0.38	0.56	0.56
	Health and safety	0.45	0.50	0.58	0.58
	Social security	0.04	0.04	0.08	0.08
	Forced labor	0.44	0.44	0.38	0.38
	Training and education	0.08	0.13	0.13	0.13
General public (e.g. local community)	Local employment	0.09	0.09	0.16	0.16
	Community engagement	0.03	0.03	0.14	0.16
	Safe & healthy living conditions	0.35	0.40	0.61	0.67
	Public opinion on the concerned materials	0.50	0.50	0.34	0.34
Government (e.g. contribution to Hong Kong and support from the Government)	Commitment to sustainability	0.17	0.17	0.67	0.67
	Contribution to economic development	0.13	0.09	0.54	0.52
	Technology development	0.00	0.00	0.31	0.31
	Support from the Government	----	----	0.38	0.38
Traders of the materials/products	Fair competition	0.50	0.50	0.38	0.38
	Social responsibility	0.06	0.06	0.17	0.15
	Supplier relationships	0.22	0.22	0.16	0.16
	Intellectual property right	0.00	0.00	0.00	0.00
Socio-environmental performance of the concerned materials/products	Materials	0.00	0.00	0.75	0.75
	Energy & water consumption	0.00	0.00	0.00	0.08
	Emissions to air, water and soil	0.00	0.00	0.00	0.06
	Solid wastes and effluent treatment	0.47	0.47	0.56	0.56
	Biodiversity (effects on local biodiversity)	0.08	0.11	0.66	0.66

[CS, crushed stone; RS, river sand; C&DW, Construction and demolition waste; WG, waste glass]

Figure 8-9 - Normalized score of sub-categories for different aggregates

8.4.3 Results interpretation

The normalized results of end-point impact categories for the studied case are given in Figure 8-10. It can be seen that natural aggregates has about 11-13% lower social sustainability than recycled aggregates in Hong Kong at the end-point category of producer responsibility. This is because the recycled aggregates have relatively higher score for some of the sub-categories (e.g. product and service labeling, use stage and end-of-life responsibility) compared to the natural aggregates. Recycled aggregates have higher end-of-life responsibilities, as they are entirely produced from waste materials. However, natural aggregates also have higher score for health and safety issue and user satisfaction (based on the quality of the materials). Similar results were found for the end-point category of human resource management. This is because the score for most of the sub-categories (e.g. fair salary, working hour, health and safety workplace for labor, social security and training) are relatively higher for recycled aggregates than the natural one. However, slightly higher score was observed for natural aggregates in the sub-category of force labor than the recycled one. The results are also consistent with other cases in the construction labor in Hong Kong according to Dong and Ng (2015).

In addition, about 11-13% higher score was observed for the end-point category of corporate social responsibility for natural aggregates. This is because the demands of aggregates are mostly fully met by importing in Hong Kong, and there is a large social network involved. Therefore, a strong business environment and supplier relationship is already in place for natural aggregates, compared to the recycled one. At the end-point category of communal development, a higher score was observed for recycled aggregates (about 23-27%) than the natural aggregates. This is because recycled aggregates can provide more local employment opportunities for the supply chain and workers/employees in the local recycling factory. In addition, the whole process involves the local community for recycling, awareness, and also promotes healthy and safe living environment through reducing waste into a value-added resource for the local community. Recycled aggregates manufacturers collaborate with different government and non-government organizations in recycling, public awareness promotion and various green activities.

In the category of societal development (e.g. contribution to Hong Kong), recycled aggregates attained very high social sustainability than the natural aggregates. This is because recycled aggregates may earn revenue through exporting the recycled products, save money by avoiding the import of materials and products, save money associated with the handling and disposal of waste materials including landfilling resources. In addition, recycled aggregates manufacturers are contributing to the society by sponsoring the research for the development of environmental technology. However, government supports to the manufacturers is minimal currently. Hence, the manufacturers are hoping for more financial incentives, loans, and development and implementation of recycled product specifications, regulations and policies from the government in Hong Kong.

Lastly, the major benefits (higher sustainability) are observed in the category of environmental responsibility of the studied materials. Compared with natural aggregates, recycled aggregates has about 75% higher social sustainability in this category, as recycled aggregates saves landfill space and associated environmental impacts. Figure 8-9 shows recycled aggregates have higher scores for the sub-category of materials (as they are produced from waste materials) and biodiversity (effects on local biodiversity for producing aggregates). However, there is no significant different for the sub-categories of energy and water consumption and solid wastes and effluent treatment (during production), and emissions (e.g. reporting, reduction target or necessary steps for reduction by the respective manufacturers) in terms of environmental responsibility.

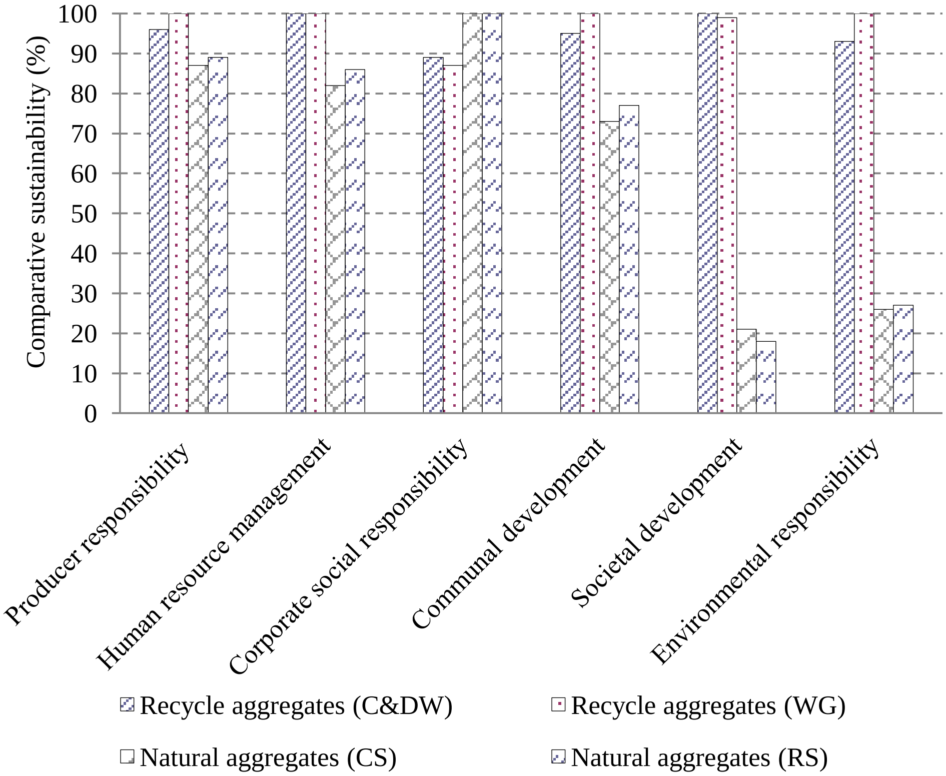


Figure 8-10 - Comparative end-point sustainability of different aggregates

The normalized SSS score obtained from the SSG-Model is given in Figure 8-11. Based on the sustainability index provided in Table 8-5, recycled aggregates have scores within the range of 0.61-0.80, indicating the level of sustainability is '*sustainable*' with grade '*B*'. This sustainable index indicates that the social performance of the products is highly positive from the perspectives of recyclers, producers, users, the general public and on economic basis. The corresponding scores for the natural aggregates are within the range of 0.41-0.60, indicating the social performance of the products is moderately positive and the level of sustainability is '*neutral*' with a grade '*C*'.

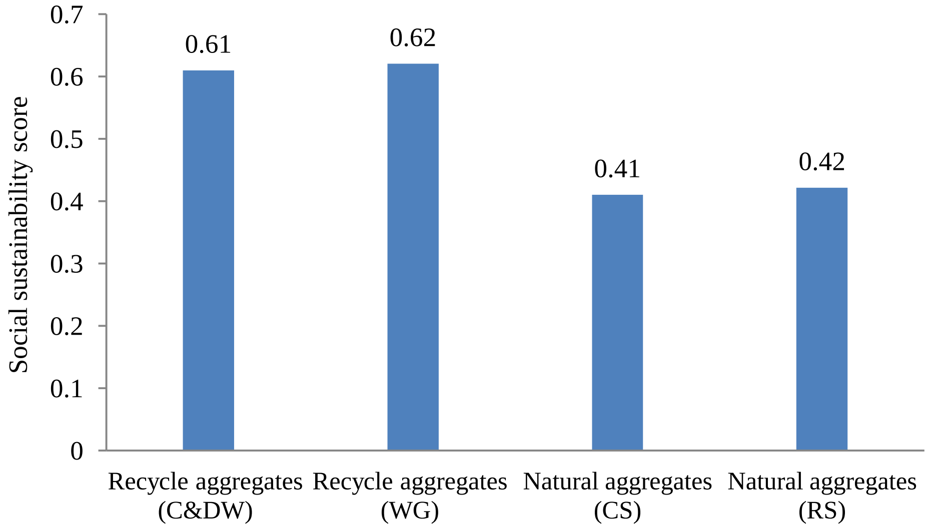


Figure 8-11 - Social sustainability of different aggregates

8.4.4 Sensitivity analysis for different weighting systems

It has already been mentioned that equal weighting for end-point categories are considered in this case study. In addition, alternative weightings were also tested to evaluate the sensitivity of the results. For six end-point categories, six alternative weighting scenarios were assessed (shown in Table 8-7). These weighting scenarios were selected to emphasize one impact category, which was given a weighting of 0.5, while the other five categories were all weighted at 0.1. The purpose of selecting these weighting scenarios was to determine whether large changes in weighting of the impact categories affect the results of SSS for aggregates.

Table 8-7 - Sensitivity analysis for different weighting factors

Weighting factor	Producer responsibility	Human resource management	Corporate social responsibility	Communal development	Societal development	Environmental responsibility
Base scenario (equal weighting)	1	1	1	1	1	1
Scenario 1	0.5	0.1	0.1	0.1	0.1	0.1
Scenario 2	0.1	0.5	0.1	0.1	0.1	0.1
Scenario 3	0.1	0.1	0.5	0.1	0.1	0.1
Scenario 4	0.1	0.1	0.1	0.5	0.1	0.1
Scenario 5	0.1	0.1	0.1	0.1	0.5	0.1
Scenario 6	0.1	0.1	0.1	0.1	0.1	0.5

The results of sensitivity analysis due to varying weighting factors are given in Table 8-8. The sensitivity results showed that SSS of natural aggregates is significantly affected by varying weighting factors of end-point categories (about 9-27% depending on the weighting scenarios 1-6, compared to the base scenario). However, less variation is found for recycled aggregates (about 0-10% compared to the base scenario). In addition, the variation of SSS is about ±15-18% for recycled aggregates compared to the natural aggregates when all scenarios are considered. However, it is expected that lower changes in the weighting factors, SSS will not affect significantly, and hence the equal weighting of end-point categories (e.g. base scenario in this case study) may be considered as suitable and reliable. In addition, no consensus has been achieved on different weighting systems in S-LCA study. Several studies have also supported that the end-point indicators could be equally weighted (e.g. Ciroth and Franze 2011; Foolmaun and Ramjeeawon 2013; Vinyes et al. 2013). However, further experts' survey to prioritize end-point impact categories would be helpful to improve the accuracy of the results.

Table 8-8 - Results of sensitivity analysis towards SSS for different aggregates

Weighting scenario	Natural aggregates (CS)	Natural aggregates (RS)	Recycled aggregates (C&D Waste)	Recycled aggregates (WG)
Base scenario (equal weighting)	0.41	0.42	0.61	0.62
Scenario 1	0.48	0.50	0.63	0.65
Scenario 2	0.45	0.47	0.61	0.62
Scenario 3	0.45	0.46	0.55	0.56
Scenario 4	0.47	0.49	0.65	0.68
Scenario 5	0.30	0.30	0.62	0.62
Scenario 6	0.31	0.32	0.59	0.61

8.5 SSG-Model validation

Validation is the key factor for the development of a new method (Jørgensen et al., 2008). However, only limited number of studies validated their models in S-LCA studies. For example, (i) further expert survey by Dong and Ng (2014), and (ii) implement inventory data to another model and vice-versa by Foolmaun and Ramjeeawon (2013), in order to validate the developed method by comparing the results. The SSG-Model can be adopted for assessing social impacts or social sustainability performance for different products (other than construction materials) and the results can be expressed in terms of the level of sustainability with grading. By following the second procedure, SSG-Model was validated and an example is provided in this section for assessing and comparing the social sustainability of tin production in China and Indonesia using the developed SSG-Model. Indicator data for tin production from these two regions was collected from Ciroth and Franze (2011). Although the inventory indicators are limited and only available at country level, it is still possible to apply the SSG-Model for comparative sustainability assessment based on the data available. The main study (e.g. Ciroth and Franze, 2011) showed that tin production has very high negative social impacts (scored 4.60 and 4.33, respectively in China and Indonesia at the scale of 6.0).

When the inventory data for tin production is used in the SSG-Model, comparative sustainability can be assessed and shown in Figure 8-12. Based on the sustainability index provided in Table 8-5, tin production in Indonesia had a score within the range of 0.41-0.60 (0.41), indicating the level of sustainability is 'neutral'. The corresponding score for tin production in China was 0.33, indicating the level of sustainability is 'unsustainable'. In addition, based on the sustainability index provided in SSG-Model, their social sustainability performance can be graded 'C' and 'D' respectively, which can be further used for socio-labeling of tin production. The result of SSG-Model is consistent with the main study in terms of social impacts and sustainability. However, the difference in percentage is mainly due to the use of different weighting systems. These results show the developed SSG-Model is not only applicable to construction materials, but also valid for other materials/products.

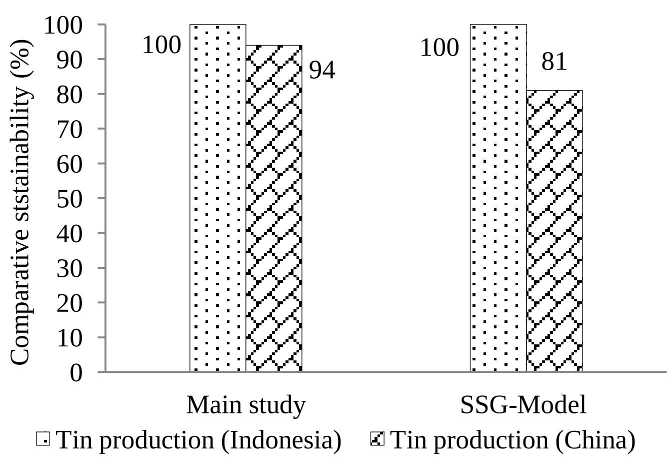


Figure 8-12- Comparative sustainability of tin production using SSG-Model

8.6 Summary

Social sustainability assessment by a life cycle approach is still under development due to its complex nature, and many challenges are still present. Case-specific studies, the improvements in quantification of the social impacts and establishment of new social impact category/sub-categories are therefore needed. Based on the developed method and case study conducted in this study, the following conclusions can be drawn:

(i) A comprehensive SSG-Model for social sustainability assessment is developed that can address the challenges of conducting social life cycle assessment of recycled materials with improvement in quantification and integration of socio-environmental impacts.

(ii) A social sustainability index with a grading system is developed for assessing the social performance of recycled materials/products.

(iii) The model can be potentially applied to assess and compare the social performance of other materials and products.

(iv) Based on the results of this case study, it is found that four sub-categories (e.g. health and safety issues of the materials, health and safety of the workers/employees, company's commitment to sustainability issue, and company's strategies on the reduction of energy and water consumption) are the most important impact sub-categories for assessing construction materials (aggregates).

(v) According to the developed SSG-Model, the use of recycled aggregates in Hong Kong can attain better performance in terms of social sustainability (31-34%) than natural aggregates.

As a first attempt of social sustainability assessment of recycled materials, the developed SSG-Model provides a framework for the construction industry to understand the social performance through a life cycle perspective.

As social indicators are interlinked with each other and social consequences are mostly variable, it is important to build in sensitivity analysis in the model which is a topic for further improvement. In addition, the integration of S-LCA method in the conventional life cycle assessment software as well as in LCA methods will also be a topic for future research.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The overall conclusions of the key findings of this study are highlighted as follows:

- According to the collected data, considered system boundary and assumptions made, the LCA results indicate that substantial net environmental benefits can be realized for producing recycled aggregates from C&D waste and waste glass, instead of imported aggregates derived from natural sources. For example, recycled fine aggregates produced from waste glass have reduced GHGs emissions by 61% compared with natural fine aggregates (river sand). This is mainly due to the longer transport distance associated with imported natural aggregates. Sensitivity analysis results show that significant environmental gains can still be achieved by producing recycled aggregates from both C&D waste and waste glass, even with 20% longer waste collection and transport distances.

- Within the considered system boundary, mix-proportions, collected data for different materials and block manufacturing processes, the LCA findings indicate that the eco-paving blocks have significant environmental gains over conventional blocks produced with natural materials. Uncertainty due to the different LCI inputs indicates that the input data are valid and the results are reliable. In addition, the LCA results show that reuse of CSW is the best management technique among other alternatives (such as reuse as recycled aggregate and cementitious material, and landfill disposal). The findings indicate that the production of partition wall blocks produced with fresh CSW and recycled aggregates significantly reduces environmental impacts (by more than 65% in the case of GHGs emission, for example) compared with conventional partition wall blocks (produced with natural materials and cement).

Moreover, recycling of waste materials, such as C&D waste, CSW and waste glass, can substantially save landfill space, which is very important for compact cities, like Hong Kong. The findings of this research demonstrate that recycling the mentioned waste materials can help to achieve higher sustainability in the construction industry.

- The valorization of waste materials such as wood waste to bio-fuel and waste glass to clinker materials for cement production is advantageous for the reduction of environmental impacts, as fossil fuel (e.g. coal) burning and clinker production are the main contributors for environmental damages in the cement industry. The LCA results show that about 2.76-13.57% of the total GHGs emissions can be potentially reduced per tonne of OPC manufacturing by replacing 10-50% of coal with the bio-fuel produced from locally generated wood wastes. The results also indicate that about 16% of energy consumption and 17% of GHGs emissions can be potentially saved for the production of Eco-GC-2 compared with that of OPC production. In addition, over 170,000 t CO_2 eq GHGs emissions can be reduced annually when adopting a combined strategy (using waste glass powder to substitute clinker and bio-fuel to replace coal). The proposed approaches can be regarded as effective measures for resource-efficient and low-carbon cement production.

- To support the decision-making process associated with LCA of concrete/concrete products with SCMs, a comprehensive review and case study were conducted for different approaches. On the basis of the review, most of the studies (more than 75%) used ‘no allocation’ (i.e. as waste) in their assessment, although the status of SCMs has shifted to by-products. Based on the LCA results of different allocation approaches, mass allocation is not suitable for concrete assessment, as very high environmental burdens are associated with concrete produced with SCMs (than concrete prepared with OPC). To some extent, economic allocation may be applicable, but temporal and spatial price variations of SCMs limit its applicability. In contrast, the system expansion approach may be the preferred approach over allocations for assessing environmental impacts of cement, concrete and concrete products, as this approach ensures the mass balance, by-products status, recycling benefits, ISO specifications and other criteria.

- SSG-Model, a single score-based S-LCA technique for assessing the social sustainability performance of construction materials was developed. For a better understanding of S-LCA, an apparent framework, system boundary and structure is provided with step-by-step data collection, data processing, data benchmarking, score aggregation processes (by appropriate weighting and normalization), and results interpretation. Similar to LCA, mid-points, end-points and single-score indicators are provided for the interpretation of results at different levels effectively. The SSG-Model consists of six categories, 30 sub-categories, six end-point categories and one single score. A social sustainability index has been introduced for turning single scores into the level of sustainability performance of materials that can be used for socio-labelling of the materials. The index was developed on the basis of five-point grading scale (e.g. A to E) meaning the level of sustainability (e.g. highly sustainable to highly unsustainable, and the corresponding score was 0.81-1.00 to 0.00-0.20).

  Comparative social sustainability performance was studied for recycled and natural construction materials to validate the model. The S-LCA results indicate that recycled aggregates had scores within the range of 0.61-0.80, indicating that the level of sustainability was '*sustainable*' with grade '*B*', whereas the natural aggregates were within the range of 0.41-0.60, indicating that the social performance of the products was moderately positive and the level of sustainability was '*neutral*' with grade '*C*'. The recycled aggregates produced in Hong Kong have better social sustainable performance than the imported natural aggregates.

9.2 Contributions of the research

The major contributions of this research are to provide guidelines for the management of several types of wastes, and to support the decision-making process regarding materials selection in the construction industry by providing practical insights and knowledge based on sustainable performance. The novel contributions of this PhD research are includes the environmental benchmarking of construction materials and products; strategies for cleaner cement production; contribution to knowledge, especially the advancement of social sustainability assessment method of construction materials, and provide the basis for the selection of environmental impacts distribution method for by-products used in construction. The key contributions are highlighted below:

- Regarding the valorization of C&D waste and waste glass to recycled aggregates, practical guidance and environmental evidence are provided to maximize C&D waste and waste glass recycling, conserve natural resources and promote sustainable waste management, and improve sustainability in the construction industry in Hong Kong.

- The environmental performance of eco-products is important in order for them to be considered as ‘eco’ or ‘green’ products. As substantial environmental benefits are observed for concrete products prepared with recycled materials (e.g. concrete paving blocks and concrete partition wall blocks), this research provides a basis to maximize recycling and utilization of waste materials, and to facilitate the construction industry to choose sustainable materials to minimize environmental damages. In addition, this research will help to promote green construction, and public acceptability and policy of eco-products.

- This research provides a practical method, guidelines and environmental evidence of cleaner cement production in Hong Kong. The proposed sustainable strategies (use of locally available waste materials) are not only able to reduce the environmental impacts from the cement industry, but also can be an important outlet for waste utilization to alleviate the severe waste management problem.

- Another contribution of this research is the knowledge development in the LCA methodology and improvement in the understanding of the LCA methods for concrete or construction material assessment when SCMs are involved. Due to the multi-functional modelling approaches of SCMs, the selection of an environmental impact distribution procedure is one of the most unresolved methodological issues in LCA. Through analyzing the robustness of different approaches using a case study, a decision matrix is provided to select the appropriate LCA approach for assessing environmental performance of the cement, concrete, or concrete products prepared with SCMs, which ensures the status of SCMs and various standards for assessment.

- The development of a social sustainability assessment tool is one of the most significant knowledge-based contributions of this research. Due to the lack of effective S-LCA tools, social sustainability assessment of construction materials was not considered during material selection. Therefore, a comprehensive, well-structured and integrated S-LCA method for construction materials was developed in this research that can be used as a standalone or complementary methodology for environmental LCA for the decision-making process. This method can promote the understanding of social sustainability, contribute to the detection of the social hotspots in sustainability aspects, and improve social sustainability in the construction industry.

9.3 Recommendations for future work

- This thesis focused on the environmental and social performance of the use of recycled materials/products. Further work is necessary to take into account the economic performance to quantify the complete life cycle sustainability of recycled materials/products.

- Although first-hand data were collected and used to establish local LCI for most of the case studies, different literature and databases (e.g. Ecoinvent, CLCD, CPM LCA, ELCD and US LCI) were used for several materials and processes as upstream data due to the lack of local LCI databases. Due to the technological and spatial variations, the LCIA results may lead to a certain level of uncertainty. Therefore, future research on the development of local LCI databases is strongly recommended in Hong Kong.

- Although uncertainty and sensitivity quality analysis due to the variation of transport distance and LCI data input were considered for some case studies, it was still inadequate as only consequences of certain uncertainties were covered. Therefore, Monte Carlo simulation is suggested to characterize the uncertainty associated with LCI data. In addition, a pedigree matrix can be applied to assess the data quality (e.g. reliability, completeness, temporal, geographical and technological correlation) in future LCA studies.

- In this investigation, the IMAPCT 2002+ LCIA method was used for most of the case studies. The characterization and normalization factors in the IMAPCT 2002+ method are mainly based upon the European context. This may lead to imprecise results in the mid-point regional impact categories, such as human toxicity, respiratory effects, ecotoxicity, acidification, eutrophication, and land occupation. In addition, the results of end-point damage categories, such as human health, ecosystem quality, climate change, and resources may be affected due to the European damage factors. Therefore, further research on the development of a LCIA method incorporating local/regional characterization, normalization and damage factors is strongly recommended for Hong Kong.

- Regarding LCA study of recycling materials and products, the complexity due to the choice of different approaches, such as attributional, consequential, cut-off, substitution, etc. needs to be resolved, as inconsistencies are clearly observed due to the use of different approaches.

- The thesis has provided the basis for the selection of environmental impact distribution methods for SCMs, and suggested that system expansion may be the preferred approach. However, further research on SCMs is recommended based on the supply and demand constraints using the system expansion approach.

- Although many aspects have been resolved in the developed SSG-Model for conducting social life cycle assessment, some issues, such as the development of social databases, integration into other life cycle methods and software, sensitivity analysis, and more case studies, are still needed for further improvement of the method.

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APPENDIX A: SUPPORTING INFORMATION FOR AGGREGATES

Table A1 - The principle of environmental impacts calculation by the IMPACT 2002+ method (Jolliet et al. 2003)

<table>
<tr><th>Method</th><th>Midpoint indicators (15)</th><th>End-point indicators (4)</th><th>Single score</th></tr>
<tr><td rowspan="15">IMPACT 2002+ method</td><td>Carcinogens</td><td rowspan="6">Human health damage unit (DALY)</td><td rowspan="15">Dimensionless, eco-point for assessing environmental burdens or impacts</td></tr>
<tr><td>Non-carcinogens</td></tr>
<tr><td>Respiratory in-organics</td></tr>
<tr><td>Ionizing radiation</td></tr>
<tr><td>Ozone layer depletion</td></tr>
<tr><td>Respiratory organics</td></tr>
<tr><td>Aquatic ecotoxicity</td><td rowspan="4">Ecosystem quality damage unit (PDF.m^2.yr)</td></tr>
<tr><td>Terrestrial ecotoxicity</td></tr>
<tr><td>Terrestrial acid. & nutrification</td></tr>
<tr><td>Land occupation</td></tr>
<tr><td>Aquatic acidification</td><td></td></tr>
<tr><td>Aquatic eutrophication</td><td></td></tr>
<tr><td>Global warming potential</td><td>Climate change unit (kg CO_2 eq into air)</td></tr>
<tr><td>Non-renewable energy</td><td rowspan="2">Resource damage unit (MJ for non-renewable energy)</td></tr>
<tr><td>Mineral extraction</td></tr>
</table>

Table A2 - Contribution of different steps to the net eco-point for aggregates production

Aggregates	Eco-point (mPt)
Natural fine (crushed stone)	
Extraction and handling	2.02
Processing	2.73
Transporting from extraction sites to the use sites	7.14
Total	**11.89**
Natural fine (River sand)	
Extraction and handling	3.15
Transporting from extraction sites to the use sites	4.73
Total	**7.88**
Recycled fine (C&D waste)	
C&D waste sorting	2.30
C&D waste transport to aggregate production site	3.48
Processing	1.71
Recycled fine transport to the use sites	2.71
Avoided impacts	-4.09
Total	**6.11**
Recycled fine (waste glass)	
Waste glass collection	6.13
Processing	4.34
Recycled fine transport to use sites	3.09
Avoided impacts due to waste glass landfilling	-10.36
Total	**3.20**

Table A3 - Damage assessment factor

Damage category	Unit	Impact category	Factor	Unit
Human health	DALY	Carcinogens	2.80E-6	DALY/kg C_2H_3Cl eq
		Non-carcinogens	2.80E-6	DALY/kg C_2H_3Cl eq
		Respiratory in-organics	7.00E-4	DALY/kg PM 2.5 eq
		Ionizing radiation	2.10E-10	DALY/Bq C-14 eq
		Ozone layer depletion	1.05E-3	DALY/kg CFC-11 eq
		Respiratory organics	2.13E-6	DALY/kg C_2H_4 eq
Ecosystem quality	PDF.m^2.yr	Aquatic ecotoxicity	5.02E-5	PDF.m^2.yr/ kg TEG water
		Terrestrial ecotoxicity	7.91E-5	PDF.m^2.yr/ kg TEG soil
		Terrestrial acid/nutria.	1.04	PDF.m^2.yr/ kg SO_2 eq
		Land occupation	1.09	PDF.m^2.yr/ m^2org.arable
		Aquatic acidification	--	--
		Aquatic eutrophication	--	--
Climate change	kg CO_2 eq	Global warming	1	kg CO_2 eq/ kg CO_2 eq
Resources	MJ primary	Non-renewable energy	1	MJ primary/ MJ primary
		Mineral extraction	1	MJ primary/ MJ surplus

Calculation of characterized impacts

The characterized impacts of category GWP for natural fine (river sand) aggregate:

GWP (%) of river sand = (Value of RS × 100)/Highest value of the category GWP

= (23× 100)/33

= 70%

Table A4 - Normalization and weighting factor

Damage category	Normalization factor	Weighting factor
Human health	141	1
Ecosystem quality	7.30E-5	1
Climate change	1.01E-4	1
Resources	6.58E-6	1

The damage factor reported in ecoinvent are normalized by dividing the impact per unit of emission by the total impact of all substances of the specific category for which characterization factors exist, per person per year (European). Default weighting factor (e.g., 1) is used.

APPENDIX B: CALCULATION EXAMPLE OF GBFS USING SYSTEM EXPANSION APPROACH

B-1 Calculation of GHGs emission for GBFS

Applying Weidema's system expansion approach to the GBFS system, the determining process for the production of GBFS is the operation of the blast furnace, with pig iron being the determinate product. The production process is typically optimised to produce pig iron, and the amount of blast furnace slag is directly related to the mass of iron being produced, and the mass of slag cannot be independently varied. Intermediate processing includes the grinding of blast furnace slag into GBFS and transport of GBFS to concrete production sites. Following Weidema's system expansion approach (the third principle, based on Table 7-3), the GBFS is attributed impacts associated with intermediate processing, as well as a credit for the avoidance of waste treatment of the granulated blast furnace slag. It should be noted that the market constraint of GBFS is not accounted in this study, and recommended for future analysis. An example of calculating GHGs emission of GBFS (per tonne) using system expansion is given below:

$$GBFS_{GHGs\ emission} = GBFS_{processing} + GBFS_{\text{transport}} - GBFS_{avoided\ impacts} \text{......(B-1)}$$

where, *GBFS processing* indicates processing of slag using electrical energy consumption, *GBFS transport* indicates GBFS transport to concrete batching plants (using inland barge and trucks), and *GBFS avoided impacts* indicates the avoidance same amount of GBFS landfilling including transportation.

Using the equation B-1, the total GHGs emission of per tonne of GBFS production using system expansion is assessed (based on the inventory data given in Tables 7-3, 7-5 and 7-6).

$$GBFS_{GHGs\ emission} = (50.51 + 11.81 - 12)\text{kg CO2 eq}$$
$$= 50.32 \text{ kg } CO_2 \text{ eq}$$

B-2 Calculation of GBFS concrete (MD-2)

Using the system expansion approach, the total GHGs emission of GBFS concrete (MD-2) production is shown in Table B2. The considerations and results are also consistent with other studies (e.g., Saade et al. 2015; Crossin 2015; Panesar et al. 2017).

Table B2. Total GHGs emission of concrete production using GBFS

Components	**GHGs emission (kg CO_2 eq)**
Cement	329.67
Fine aggregates	22.44
Coarse aggregates	29.92
GBFS	7.15
Admixture	6.44
Concrete production	1.58
Total	**397**

APPENDIX C: SUPPORTING INFORMATION FOR S-LCA METHODOLOGY DEVELOPMENT AND CASE STUDY

C1: Inventory indicators used in this case study

Category 1 (stakeholder): Producer of the concerned materials/products

1.1. Sub-categories (impact): Health and safety
Indicators: 1. Level of potential safety with the product for transport and handling? 2. Is the product harmful from a health perspective through its lifecycle? 3. Is there any safety information or sign of the products? 4. Is there any consumer complaint about health and safety issues? 5. Total number of user complaints per year about health and safety issues. 6. Is there any quality of labels of health and safety requirements? 7. Is there any a potential emission or leakage or discharge during utilization of the products through it life cycle? 8. Is there any potential measure to prevent it?

1.2. Sub-categories: Use stage responsibility
Indicators: 1. Is there any policy available for use stage responsibility by the relevant materials producer? 2. Any future risk of accident/health damage for the final user imposed by the materials?

1.3. Sub-categories: Product and service labeling
Indicators: 1. Is the product suitably labeled with regards to it component parts or ingredients? 2. Compliance with international accounting practices and regulatory requirements (transparent way). 3. Certification standards, labels, and special indices that may be used to provide information about the performance are transparent? 4. Is there any publication of a sustainability report about social and environmental life cycle impact assessment? 5. Certification/label the organization obtained for the product, or company sustainability rating (e.g. Corporate Sustainability Index) are transparent? What level?

1.4. Sub-categories: End-of-life responsibility
Indicators: 1. Are there any management efforts to address end-of-life service of the products such as disposal, reuse or recycling, 2. Level of management attention to end-of-life impacts of the products, 3. Do producers have any buy back and recycle or safely dispose of wastes scheme?

1.5. Sub-categories: User satisfaction (based on quality)
Indicators: 1. Do the materials/products maintain international/national standards on the quality? 2. What is the level of standards of the concerned materials/product? 3. Is there any practice related to user satisfaction (surveys measuring customer satisfaction)? 4. Level of user satisfaction on the materials/products

Category 2: Worker/employee

2.1. Sub-categories: Fair salary and employee characteristics
Indicators: 1. What are the personal characteristics of the workforce (age, sex, nationality, etc.)? 2. What is the average hourly salary?

2.2. Sub-categories: Hours of work
Indicators: 1. What is the normal working hour per week of the company? 2. Is there any over-time scheme for employee? 3. What is the minimal wage per hour for over-time? 4. Is there any mutual agreement between employee and company for over-time scheme?

2.3. Sub-categories: Health and safety
Indicators: 1. Level of safe and healthy workplace. 2. Number/ percentage of injuries or fatal accidents in the organization in last one year. 3. Level of safety and health concerning employee's accommodation and food (on-site). 4. Is there any formal policy concerning health and safety (e.g. accident insurance, medical insurance/reimbursement scheme)? 5. Is there any health and safety committee available in the factory/industry? 6. Recorded case of health and safety issues inside the industry in the last 1 year.

2.4. Sub-categories: Social security (and social benefit)
Indicators: 1. Is there any "interest of profit" scheme for the employee? 2. Is there any bonus scheme for the employee? 3. Is there any social benefit scheme (e.g. retirement, disability, dependents, survivor's benefits, paid maternity and paternity leave, paid sick leave)? 4. Difference of social benefits between permanents and part-time/temporary employee.

2.5. Sub-categories: Forced labour
Indicators: 1. Is there any forced (e.g. compulsory labor), although it is paid or not? 2. Is there any abuse of work (mental or physical harassment)?

2.6. Training and education
Indicators: 1. Is there any training or education scheme for the employee skill improvement? 2. Average hours of training per year per employee, and by employee category. 3. Percentage of employees receiving regular performance and career development reviews.

Category 3: Traders of the materials/products

3.1. Sub-categories: Fair competition
Indicators: 1. Is the company performing unfair business practices (e.g. abuse of market position, cartel, anti-competitive mergers, price-fixing, and other collusive actions which prevent competition)? 2. Is the company's policy compliance with national legislations preventing those unfair business practices?

3.2. Sub-categories: Intellectual property right
Indicators: 1. Is there any intellectual property (IP) right of the materials/product? 2. Is the company using local IP?

3.3. Sub-categories: Supplier relationships
Indicators: 1. Level of relationship with the suppliers? 2. Is this relations comply mutual activities, co-operations, agreements that regulate the exchanges, trade and relation among different organizations? 3. Is the absence of coercive communication with suppliers and reasonable volume fluctuations? 4. Is the payment on time to suppliers?

3.4. Sub-categories: Promoting social responsibility
Indicators: 1. Has any initiative to promote social responsibility among its suppliers and through its own actions by monitoring, auditing and training efforts? 2. Has any membership that promotes social responsibility along the supply chain? 3. Level of social company's social responsibilities?

Category 4: General public

4.1. Sub-category: Community engagement
Indicators: 1. Is there any direct involvement in community initiatives and/or through financial support of community projects (e.g. Earth Day activities, recycling initiative, etc.). 2. Total number of meetings with community stakeholders last year regarding products promotion/ social awareness/ sharing knowledge, etc? 3. Current level of community engagement? 4. Community engagement in recycling and economic benefits.

4.2. Sub-category: Local employment
Indicators: 1. Is there any initiative of local community development by training local employees in technical and transferable skills? 2. What is the company's policy of local employment (e.g. local supplier networks, local labor, etc.)? 3. New job creation.

4.3. Sub-category: Safe and healthy living conditions
Indicators: 1. Does the product contain any safety and health impacts issue for the community (using of the product)? 2. Is the product related to discharge polluted water/air, sound pollution or other hazardous materials which brings health issue to the local community? 3. Level of company's operational accident (equipment accidents) and structural failure which is potential to safety issue to local community. 4. Level of company's management effort to minimize health and safety issue. 5. Reducing potential health hazards (by reducing waste). 6. Reducing nuisance conditions (by reducing waste). 7. Increase property value (nearby landfill).

4.4. Public opinion on the concern materials/products

Indicators: 1. Reported case of complain for the concerned materials/product in the last 1 year? 2. Does the general public aware regarding the concerned materials/product? 3. Level of public satisfaction. 4. Level of public acceptability.

Category 5: Government and society

5.1. Sub-categories: Commitment to sustainability

Indicators: 1. Is there any company's commitment towards sustainability issues? 2. Is there any collaboration of the different sector/stakeholder regarding sustainability? 3. Is there any legal obligation on public sustainability reporting?

5.2. Sub-categories: Contribution to economic development

Indicators: 1. How healthy is the company? (In terms of manpower, economic infrastructure, investment, etc.). 2. How stable is the company in terms of size and operations? 3. What extent the organization/product contributes to the economic development of the country (e.g. revenue, create jobs, provide education and training, make investments, or forward research)? 4. Extent of revenue earning by the sector. 5. Saving money due to import (materials). 6. Taxation (from the employee and mafacturer). 7. Reducing waste volume and associated collection and transport costs. 8. Saving disposal land and associated costs.

5.3. Sub-categories: Technology development

Indicators: 1. Is the company containing any investment scheme in technology development/ technology transfer/ individual or joint research for efficient and environmental sound technologies? 2. Level of company's technological innovation to improve the product?

5.4. Sub-categories: Support from the government

Indicators: 1. What types of support are available /getting from the Government? 2. The scale of support is currently provided for the relevant industry. 3. What types of supports are expected from the government towards sustainability?

Category 6: Relevant stakeholders (socio-environment)

Sub-category 1: Materials (use of natural & recycled materials)

Indicators: 1. Raw materials (approximate % of using recycled/renewable materials). 2. Raw associated process materials (e.g. materials that are needed for the manufacturing process but are not part of the final product, such as lubricants for manufacturing machinery). 3. Semi-manufactured goods or parts, including all forms of materials and components other than raw materials that are part of the final product. 4. Materials for packaging purposes, which including wood, paper, cardboard, plastics & others.

Sub-category 2: Energy use & water consumption

Indicators: 1. Energy consumption within the organization. 2. Sources of electricity. 3. Energy consumption outside of the organization. 4. Reduction of energy consumption. 5. Water (Total water withdrawal by source). 6. (%) of water recycled and reused?

Sub-category 3: Emissions

Indicators: 1. Emissions inside the industry (reported or not). 2. Emissions from outsides the industry (emissions related to transport of goods). 3. Emissions reduction target (by re-designing the process/products or operation, renewable, etc).

Sub-category 4: Solid wastes and effluents

Indicators: 1. Effluents discharge (treated?). 2. Solid waste management. 3. Hazardous waste management and significant spills. 4. Reported case of complain by local residents. 5. Potential effects on local community due to solid waste and effluents.

Sub-category 5: Biodiversity

Indicators: 1. Surrounding area of the industry. 2. Significant impacts of activities, products, and services affects on biodiversity. 3. Habitats protection or restoration. 4. Conserve natural resources.

C2: Benchmarking

Table C2 – Example of indicators benchmarking
(Two sub-categories for recycled aggregates from C&D waste)

Sub-category	Indicators	Responses	Benchmarking (best practice) and Significance		Achieved score*	Significance
Characteristics of worker/ employee and fair salary	Age of worker (year)	21-40	18-65 years (HKLD 2014; Dong 2014)	0% child labor	1	No child labor involved
	Sex (female ratio)	80:20	Equal opportunity (GRI 2013; WB 2012)	No discrimination; as much as possible	1	No sex discrimination
	Nationality (origin)	50:50	Equal opportunity (GRI 2013; HKIHR 2001)	No discrimination as race, origin, etc.	1	No discrimination on origin
	Average hourly salary	>40 HK$/h	HK$ 32.5/h (HKLD 2014); 3.87 US$/h (Dong 2014)	The wage level should ensure a decent standard of living (HKIHR 2001)	1	Highly compatible with standards
Hours of work	Normal working hour per week	51h/week	47 h/week (5 days in week) (Dong 2014)	Depend of sectors	0.75	Higher than the standards (8%)
	Over-time scheme for worker	N/A	Paid public holiday: 12 days/year, and based on the requirements and regulations of company (HKLD 2014)	Contract should follow the national labor laws for over-time (HKLD 2014)	N/A	--
	Minimal wage per hour for over-time	N/A	1.5-2 times normal hourly wage (HKIHR 2001)	Depends on the time of over-time	N/A	--
	Type of contract for over-time	N/A	Mutual agreement between employee and company for over-time scheme (HKLD 2014); special allowance (e.g. travel, meal, special duty, etc.) on special circumstances (HKIHR 2001)	Contract should follow the national labor laws for over-time (HKLD 2014)	N/A	--

[*Scored based on Table 3; N/A, not applicable in this particular case]

Relationship of characterization and benchmarking

The linkage between characterization and benchmarking can be expressed by following equation:

$$Ch_i = BI_i$$

Where, Ch_i is the characterization result of Indicator i, B is the benchmarking (using Table 8-3), I_i is the value of Indicator I, Ch_i result should be within 0 to 1.

Example: The standard age limit for worker is about 18-65 years in Hong Kong. Based on the response, age range of the worker is 21-40 years, which is 'highly compatible' with national labour laws in Hong Kong. Based on the Table 3, the score of 'highly compatible' (with national and international laws and standards) is '1'. Therefore, Ch_{age} score of indicator 'age' is 1.

C3: Impacts calculation

1. Calculation of normalized score of sub-category: Two examples are provided as example.

1.1. Sub-category: Fair salary and worker characteristics
Normalized score of Fair salary and worker characteristics (SS_F) sub-category can be calculated by using equation 8-1:

$$SS_F = \frac{[(1 \times 0.75) + (1 \times 0.75) + (1 \times 0.75) + (1 \times 0.75)]}{4}$$
= 0.75

1.2. Sub-category: Hours of work
Normalized score of hours of work (SS_W) sub-category can be calculated by using equation 8-1:

$$SS_W = \frac{[(0.75 \times 0.75)]}{1}$$
= 0.56

2. Calculation of normalized score of end-point category

End-point category: Human resource management

Normalized score of human resource management (SE_H) end-point category can be calculated by using equation 8-2:

$$SE_H = \frac{[\mathbf{0.75} + \mathbf{0.56} + 0.58 + 0.08 + 0.38 + 0.13]}{[0.75 + 0.75 + 1 + 0.5 + 0.5 + 0.5]} \qquad (2)$$

= 0.62

3. Calculation of SSS

The net score of social sustainability (SSS) of recycled aggregates production from C&D waste can be calculated by using equation 8-3:

$$SSS = \frac{[0.65 + \mathbf{0.62} + 0.47 + 0.72 + 0.63 + 0.56]}{[6 \times 1]} \qquad (3)$$

= 0.61

[Bold figures are shown in the above calculations as example]

C4: Hotspot identification

https://docs.google.com/forms/d/1tzXHFttGTatAa3QPH9w06kMxfIvzBDYs0RJjRCkbEW4/viewform?c=0&w=1&fbzx=7660546982898501905

Title: Social sustainability assessment; a comparative case study on recycled construction products

<u>Expert survey for key factor identification</u>

Abstract: The objective of this survey is to find out the social impacts associated with the manufacture and use of construction materials in Hong Kong. Several types of construction materials, included cement, natural aggregates, recycled aggregates (recycled C&D waste and recycled glass), and recycled products (e.g. eco-blocks) are included in this study.

The following categories of target groups/sectors and sub-categories of social impacts are proposed by UNEP/SETAC, Hong Kong Sustainability Index and Global Reporting Initiative (GRI) for conducting social lifecycle assessment (S-LCA) of the materials/products. However, the importance of the different social impact categories may be different in different geographic regions. We would like to seek your views on their relative importance by completing the simple questionnaire attached.

Thank you for your valuable contribution.

With best regards,

Md. Uzzal Hossain, PhD Candidate
Email: 1390 @ ; 9276

Prof. C.S. Poon (Supervisor)
Email: cecspoon@ ; 2766

(Please put a tick "√" mark on the relevant section)

Question: What is your view on the relative importance of the listed sub-categories in the perspective of the concerned sectors (Please try to assess ***All*** sub-categories even you are not affiliated with the sector)?

Concerned Sector	**Sub-categories**	**Importance**				
		(1)	**(2)**	**(3)**	**(4)**	**(5)**
Producers of the concerned materials/products	Health and safety					
	Use stage responsibility					
	Product and service labeling					
	End of life responsibility					
	Transparency					
	User satisfaction (based on quality)					
Worker/Employee of the relevant industry	Fair salary					
	Working hours					
	Health and safety					
	Social security					
	Forced labor					
	Training and education					
General public (e.g. community)	Local employment					
	Community engagement					
	Safe & healthy living conditions					
	Access to materials resources					
	Access to immaterial resources					
	Public opinion on the concerned materials					
Government & society (e.g. contribution to Hong Kong and support from the Government)	Commitment to sustainability					
	Contribution to economic development					
	Technology development					
	Support from the Government					
Suppliers of the materials/products	Fair competition					
	Social responsibility					
	Supplier relationships					
	Intellectual property right					
All stakeholders (Environmental performance of the concerned materials/products)	Materials (use of natural & recycled materials)					
	Energy & water consumption					
	Emissions to air, water and soil					
	Solid wastes and effluents treatment					
	Biodiversity (effects on local biodiversity)					

Scale of the prioritization: 1, least importance; 5, most importance

General information of the Experts

Name of the institution:

Position:

(Please prioritize the sub-categories in each sector based on your expertise on the materials/products producing your institution or expertise on handling/work/research).