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Influence of waste materials on buildings' life cycle environmental impacts: Adopting resource recovery principle

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ABSTRACT

Buildings are responsible for a significant natural resources diminution and emissions to the environment. Thus, the building industry has become a global target for reducing environmental impacts and curbing resource depletion. Concerning the rapidly growth of buildings, life cycle assessment (LCA) is increasingly used for assessing and mitigating the associated environmental impacts from material selection to the whole building systems. However, many of the previous studies have focused on the impacts assessment from buildings within a restricted system boundary, especially lack of consideration of several critical factors when assessing the whole building, such as wastage level of raw materials during building construction and the disposal impacts, renovation and replacement of components of building and their treatment, and waste treatments during building demolition. As the industry is shifting from linear to circular, the consideration of those factors are essential for ensuring waste reduction, resources recovery and resource-efficient construction, not to mention about increasing the accuracy of such assessment. Therefore, the present study was conducted to assess the environmental impacts of the mentioned aspects at different life cycles of building by LCA. The results were then critically discussed after identifying the contribution of waste materials at different stages of building to the total impacts. The potential sustainable strategies for waste treatments during the construction, operation and end-of-life stages of building were then highlighted to help lay important foundation for adopting circular economy principle in the building industry and establishing benchmark for future reduction.

1. Introduction

The construction industry is one of the main contributors to environmental burdens, consuming significant amount of non-renewable bulk resources and raw materials, and causing considerable waste streams (Faleschini et al., 2016). While the industry plays an important role for economic contribution and social development throughout the world (Vitale et al., 2017), the industry also contributes to about 40% of depletion of natural resources, 18% of greenhouse gas emissions, and 25% of wastes globally (Teh et al., 2018).

The building sector consumes a substantial amount of resources and is, therefore, one of the largest contributors towards environmental impacts (Atmaca, 2016; de Klijn-Chevalerias and Javed, 2017). For example, buildings are responsible for about 40% of the total energy consumption and 36% of the total CO_2 emissions worldwide (Pal et al., 2017). Therefore, increasing attention has been devoted in the building sector to minimize the environmental impacts globally (Hossain and Poon, 2018a).

In addition to the selection of low impact, sustainable and durable materials, consideration of sustainable management of construction and demolition (C&D) waste is also important to minimizing the disposal problem and reducing the associated environmental burdens, as a huge amount of land is currently occupied for the disposal of those materials, leading to an increase in the ecological footprint of the sector (Faleschini et al., 2016). Due to the volume, nature and high recycling potential, C&D waste is a priority waste stream in many part of the world including the European Union (EU) (Vitale et al., 2017; Borghi et al., 2018). Because C&D waste puts huge pressure on depleting landfills and affects the environment adversely (Butera et al., 2015; Bovea and Powell, 2016; Akinade et al., 2018), it is important to improve the sustainability by adopting design solutions with the aim to optimize resource usage and minimize waste material generation, as restated in the EU action plan for a circular economy (CE) (Vitale et al., 2017). Therefore, further policies and strategies are needed for resource-efficient management of C&D waste as the current trends are to the landfill or downcycling practices (Di Maria et al., 2018), and thus, EU proposed a new framework for this waste in the CE package (Gálvez-Martos et al., 2018).

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CE is a sustainable development strategy that aims at improving the efficiency of materials and energy usage. The desire for CE and optimal material reuse calls for the need to improve techniques for whole-life performance assessment of buildings (Akanbi et al., 2018). When there are resources scarcity and supply shortage, industrial symbiosis plays a significant role to lower the environmental impact and promote green economic growth - i.e. the system can help link industrial development and carbon reduction (Pauliuk, 2018). However, CE is relatively a new model that promotes maximum reuse / recycling of materials and components in order to reduce waste generation to the largest possible extent (Ghisellini et al., 2018). CE also necessitates a systemic shift due to the different concepts and understanding by integrating the economic prosperity and environmental quality, and its impacts on social equity and future generations (Kirchherr et al., 2017). However, developing guidelines for CE implementation and choosing CE indicators are still in the early stages and unclear, and should be based on the life cycle analysis (LCA) and material flow analysis (Pauliuk, 2018; Stephan and Athanassiadis, 2018).

Considerable efforts have been put forward in building environmental research using LCA throughout the world. For instance, in France (Hoxha et al., 2017), Belgium (Buyle et al., 2018), United Kingdom (Cuéllar-Franca and Azapagic, 2012), United States (Nadoushani and Akbarnezhad, 2015), Belgium, Portugal, Sweden (Rossi et al., 2012), Turkey (Atmaca, 2016), Hong Kong (Dong and Ng, 2015; Gan et al., 2017), Spain and Colombia (Ortiz-Rodríguez et al., 2010), Italy (Vitale et al., 2018), China (Guo et al., 2017; Yang et al., 2018), South Korea (Roh and Tae, 2017).

In addition, several recent studies have contributed to building LCA research significantly through methodological improvements, data quality and other important aspects. For example, Moncaster et al. (2018) studied the methodological variations including the temporal and spatial differences as well as the physical disparities in embodied carbon coefficients chosen. Their study concluded that any variations in methodological choices can substantially influence the overall results, and a transparent calculation of building LCA is therefore imperative. According to Giesekam and Pomponi (2018), practitioners' knowledge is still limited and guidance is still lacking in several aspects of embodied carbon assessment of buildings, *viz.* the lack of access to products and construction data, lack of standardize assessment methodology, variability of results among different studies, etc. Pomponi and Moncaster (2016) examined carbon mitigation in buildings based on LCA. Through a meta-analysis, the study concluded that LCA studies of buildings were incomplete and short-sighted, as most of them only focused on the manufacturing stage without covering the impacts related to the occupancy and end-of-life of buildings. The study identified several elements which can help develop a low carbon built environment, e.g. the use of low carbon materials; better design; reuse of embodied carbon intensive materials; stronger policy implementation; etc. Similarly, De Wolf et al. (2017) performed an analytical review on the embodied carbon of buildings based on academic and professional literature with a desire to reduce the embodied carbon emissions of buildings. The study postulated that improving the data quality as well as developing a transparent and simplified method of assessment to encourage industry collaboration are necessary to improve the accuracy of assessment.

By analyzing a large number of case buildings, Rasmussen et al. (2018) concluded that a common standard may not suit all purposes despite it can provide general guidance of practice. Instead, the study pointed to a high degree of standardization to pave way for certification and the development of building regulations. Uniform definitions and templates with clear description of system boundaries and complete inventory coupled with quality data are necessary for transparent assessments. Pomponi and Moncaster (2018) scrutinized the embodied carbon assessment in buildings by considering the data used and the methodological assumptions adopted in different studies. The study discovered remarkable differences due to data variability, and this can lead to 284-1,044% variations of embodied carbon coefficient for the manufacturing of main structural building materials. The study suggested quantifying the environmental impacts of construction and the end-of-life activities in a harmonized manner and by employing more detailed data to fully understand the scenario or uncertainty caused by data variability. However, the LCA results can be significantly affected or become unreliable due to some critical factors including the considerations of waste material disposal or management at the different stages of building, and uncertainties due to material selection and data sources, notwithstanding that LCA is widely adopted in evaluating the environmental impacts of buildings (Hafliger et al., 2017; Hoxha et al., 2017).

The consideration of the aforesaid factors, especially the management of wastes during the construction and use phases of new building and building renovation, are important for enhancing the accuracy and comprehensiveness of assessment, although some studies only considered the end-of-life scenario of building without paying much attention to material recovery. The critical consideration of C&D waste management, as well as resources recovery at different stages can influence the overall environmental performance of buildings significantly. However, many previous studies have focused on the impacts assessment from buildings within a restricted system boundary, without considering the wastage level of raw materials and the disposal impacts; renovation and replacement of components of building and their treatment; and waste treatments during the end-of-life of building. As the industry is shifting from a linear to circular form, the consideration of those factors are essential for ensuring waste reduction, resource recovery and resource-efficient construction, as well as to increase the accuracy of such assessment.

This study, therefore, aims to assess the environmental impacts of the abovementioned aspects at different life cycle stages of building through LCA so as to improve the accuracy and comprehensiveness of assessment. Apart from existing strategies, a potential sustainable resource recovery principle is also proposed to integrate with CE to help reduce the environmental impacts and conserve building resources. Therefore, several potential contributions are expected from this study, which include (i) an improvement in the accuracy of building environmental assessment, (ii) a greater utilization of waste materials generated at different stages of buildings, and (iii) the development of a framework for integrating CE into buildings, and (iv) an improvement in the way to adopt resource recovery principle in buildings to enhance the sustainability performance of buildings. More importantly, the framework and research method proposed in this study can be adopted in other regions to encourage the adoption of CE and resource recovery principle into buildings.

2. Framework for resource recovery and CE into buildings

Due to the importance of the building industry, building LCA research have considerably progressed over the last years, where researchers have contributed significantly to resource-efficient and low carbon building construction (some of them are already mentioned in the introduction section). Yet, a recent review has highlighted that about 69% of the studies did not to consider waste management and recovery in their assessment, despite 27% of the studies considered only the end-of-life waste treatment (Hossain and Ng, 2018). The consideration of C&D waste treatment and resources recovery at different stages of buildings can significantly influence the environmental performance. As a result, it is necessary to critically consider C&D waste treatment and resources recovery in building LCA research, and CE principle has great potential to be adopted effectively to help reduce the environmental impacts and reduce resource consumption. Tingley et al. (2018) proposed four design strategies, namely: building reuse; materials reuse; deconstruction and materials reuse; and adaptability. These four design strategies are central to the CE approach of buildings, as they focus on maintaining the value of material assets.

The principles of CE are mainly based on the industrial ecology theory – a framework which is useful for the design of construction projects in a sustainable manner through efficient use of materials; effective design and process flow; energy reduction; and resource recovery (Núñez-Cacho et al., 2018b). In the CE framework, traditional 'end-of-life' concept is replaced by maximum recovery of materials in inter and intra systems, as it operates at the micro to macro levels with the aim to accomplish sustainable development (Nuñez-Cacho et al., 2018a). The CE principles are well aligned with the global resources management concept in future, as the framework supports preservation of virgin resources and optimal utilization of resource through the manufacturing of reusable products and minimization of waste generation (Moreno et al., 2016). Several studies highlighted the importance of CE adoption as a mean to reduce environmental impacts, waste material generation, save virgin resources, and maximize the recycling of secondary resources (Nuñez-Cacho et al., 2018a).

While the building industry consumes a huge amount of natural resources and generates enormous waste materials, the CE framework can be effectively adopted to reduce the environment impacts of this sector. For this reason, serious attention has been attributed to this sector to lower the associated environmental impacts and resource consumption (Khoshnava et al., 2018). Global resource scarcity is the driving force for the development of new technologies to recover waste for inputting into the new production cycle (Van Dijk et al., 2014). However, several factors including the undefined system boundary, types of recycling considerations (closed-loop or open-loop), lack of knowledge of the type of CE indicators, etc. could hinder its practical application in the building sectors (Hossain and Ng, 2018). Moreover, studies regarding the practical adoption of CE in building LCA is currently sparse and at an early stage of development, despite some studies have made significant progress in this field of research. For example, Núñez-Cacho et al. (2018b) identified the main dimensions of measuring scale for buildings when CE is adopted, including materials; energy; emissions; water; waste; and resource recovery. Dieterle et al. (2018) highlighted that a cradle-to-cradle LCA approach is better aligned with the CE settings. Some studies preferred a closed-loop system for CE adoption (Niero and Olsen, 2016), whereas some are in the open-loop system (Deschamps et al., 2018). Eventually, it depends on the types of materials, way of recycling and potential utilization in secondary products. Haupt et al. (2017) pointed out that the recycling rate can be a good performance indicator under the CE settings for the supply of alternative materials from secondary resources, as recycling rate (for both open and closed-loop recycling systems) can provide useful information for quantifying the circulated materials based on materials flow analysis.

Based on the above considerations, a framework for adopting resource recovery and the CE principles in buildings is proposed (shown in Fig. 1) and implemented in this study (details are presented in Section 3). Under the proposed framework, the generation of waste materials at the three stages of buildings (i.e. construction, use and renovation, and end-of-life stages) with their treatments including resource recovery through the closed-loop and open-loop systems, their potential utilizations, and the consideration of main dimensions and performance indicators are highlighted. For recovered materials utilizations, substitution ratio can be used for the closed-looped system, whereas replacement co-efficient (by considering the quality and market availability of materials) can be adopted for the open-looped system based on the materials flow, when performing building LCA under the CE context (Hossain and Ng, 2018). This will help increase the accuracy of assessment through the identification of any potential in resource recovery, and thus save valuable natural resources ultimately. Furthermore, any technological and social challenges, environmental and economic viability, and political influences should be taken into consideration to ensure a sustainable transition towards a circular built environment (Pomponi and Moncaster, 2017). However, the social, policy and economic behaviors as well as their influences were not considered in the proposed framework.

3. Study methodology

As the design of LCA research pertinent to waste materials at different building stages is complex due to variety of materials, lifespan of building, and different considerations of waste management, a systematic framework of methodology used in this study is shown in Fig. 2. After defining the aim of the study, data regarding the waste generation and their composition at different building stages (considered the three stages in this study) were collected. The existing management strategies of these waste materials were identified, and alternative strategies were developed based on previous studies, where the framework of the proposed resource recovery and the CE principles were adopted. It should be noted that huge amount of data was collected (with several assumptions and considerations) in inventory analysis for conducting LCA of such complex systems. After that, the LCA approach used in the study was specified and justified. After specifying the life cycle impact assessment method and selecting the impact indicators, results obtained based on the above data and considerations were analyzed for both the base and alternative scenarios comparatively. The details of each step and process are described in the following sections.

3.1. *Waste materials flow analysis of building*

In order to evaluate the waste material flow of building, three stages of analysis were conducted in this study.

3.1.1. *Construction stage*

Construction waste generation rate and compositions can vary with different stages of construction process (Hossain et al., 2017). Therefore, the average compositions of construction waste at different stages of construction (e.g. the early, mid and finishing stages of construction for different sites) were collected based on a recent report in Hong Kong (CIC, 2017), and shown with the existing management practices in Table 1. According to the results of site visits which aimed to estimate the construction waste generation in building construction, the generation rate (bulk waste) was 0.48-0.60 m^3/m^2 of the construction floor area. Therefore, the total amount of waste generation was calculated based on the generation rate and weight of the materials (considering the construction waste bulk density is about 1400 kg/m^3 with reference to Coelho and de Brito (2013) and Ulubeyli et al. (2018)).

3.1.2. *Renovation stage*

As a complex system, buildings are often undergoing various changes in terms of renovation. Considering a 75-year service life of buildings in Hong Kong (Chiang et al., 2016), typical replacement of principal elements with their number of replacement over the entire life of building are shown in Table 2. The production and transportation of these elements are included in this LCA along with their disposal strategies after renovation. Ecoinvent databases were used for collecting the upstream data for ceramic tile, emulsion paint, sealing materials, and hardwood doors production. Based on the renovation of typical flats, the average per unit (m^2) is calculated according to Chiang et al. (2016).

3.1.3. *End-of-life stage*

End-of-life waste generation was estimated based on the principal materials used in the building systems (Heinonen et al., 2016), where some of the materials were estimated based on the materials consumed for building construction with a case-specific data and others were collected from different literature. Typical end-of-life waste generation with their existing management practices in Hong Kong is shown in Table 3.

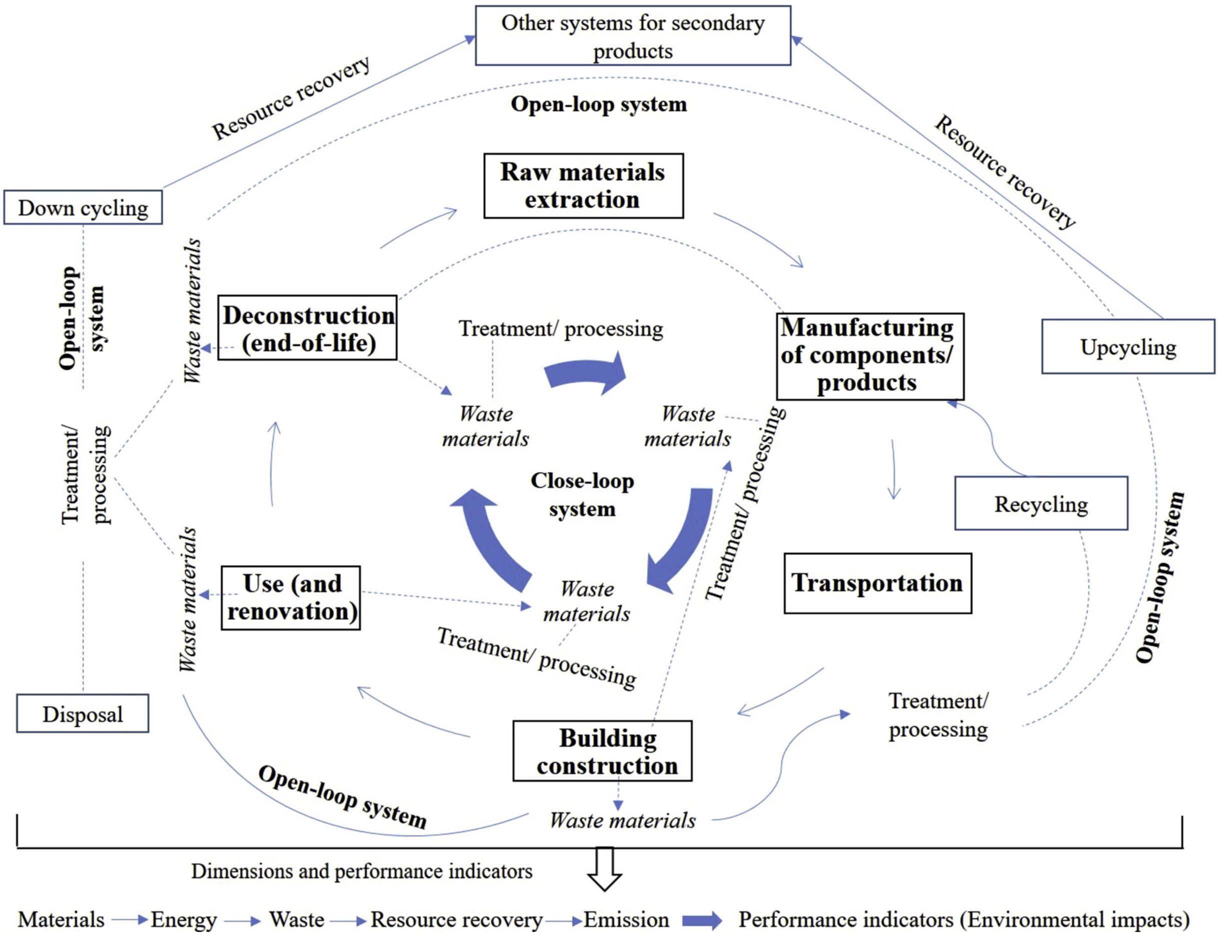
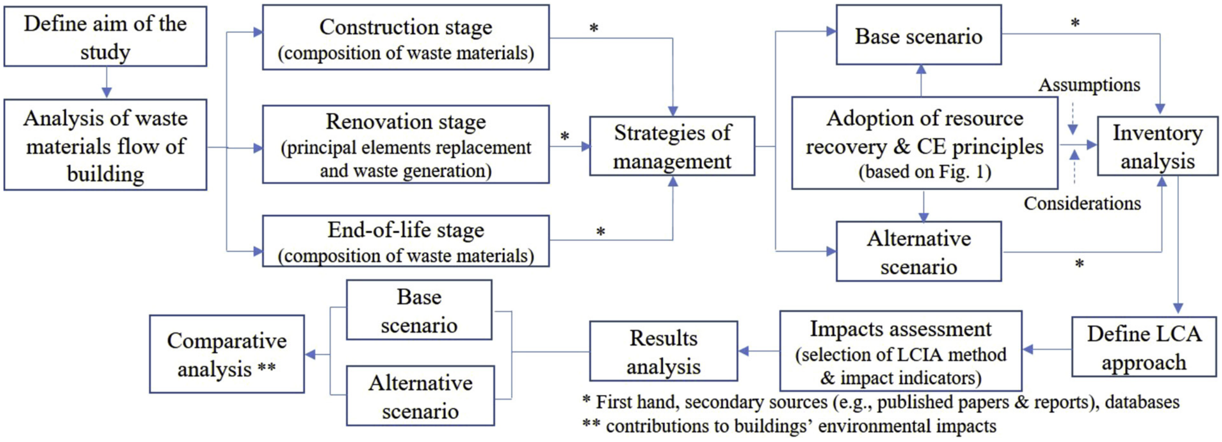


Fig. 1. Integrated framework of resource recovery and CE adoption into buildings.



* First hand, secondary sources (e.g., published papers & reports), databases

** contributions to buildings' environmental impacts

Fig. 2. Framework of the study methodology.

Table 1
Average composition of construction waste.

Waste type	Composition (%)	Existing management strategies
Non-inert waste	*47*	
Wood and timber	36	Landfill
Metal	6	Recycled
Paper and cardboard	2	Landfill
Plastics and rubber	2	Landfill
Other non-inert	1	Landfill
Inert	*53*	*Public fill*
Total	100	

Table 2
Typical replacement of building elements in Hong Kong.

Element / material	Service life (years)[a]	Number of replacement over the service life of buildings	Existing management strategies
Ceramic tiles	20	3	Public fill
Emulsion paint	5	13	Landfill
Silicone seal	10	6	Landfill
Hardwood solid-core doors	20	3	Landfill

[a] Chiang et al., 2016.

Table 3
Typical waste generation at end-of-life stage.

Element / material	Waste generation (kg/m^2)	Existing management strategies
Concrete[a]	1731	Public fill
Steel and iron[a]	132.75	Recycled
Ceramic tiles [b]	29.45	Public fill
Wood [c]	3.68	Landfill
Copper [c]	0.71	Recycled
Plastics (PVC, polyethylene, and polystyrene) [c]	7.29	Landfill
Glass [c]	1.35	Landfill

[a] Estimated.
[b] Chiang et al. (2016).
[c] Vitale et al. (2017).

3.2. The scope of the study

3.2.1. Contribution to the total impacts

The first part of the scope of this study aimed to comprehensively evaluate the total environmental impacts associated the waste generation at different stages of building, including the construction, renovation (including the renovation impacts) and end-of-life stages of a building.

3.2.2. Resource recovery principles

The second part aimed to evaluate the influence on environmental impacts of building construction due to the circulation of waste materials with the view of adopting the CE principle and industrial symbiosis. The study included all stages of the life cycle of building construction waste, i.e. from its generation (i.e. building construction sites) to its disposal in landfills or public fills, and its transformation into recycled materials and valorization into secondary products / materials. Hence, the considered system boundary was ‘cradle-to-grave’ with a functional unit of 1 m^2 of building when adopting CE into considerations (Fig. 3). The substitution approach due to the utilization of recovered waste materials was used in the LCA study.

3.2.3. Scenario analysis

The study aimed to comprehensively evaluate the contribution of waste materials to environmental impacts of building at various stages. The environmental impacts were evaluated based on the data and considerations for waste generation and management at different stages of building (showed in Tables 1–3, and explained in Section 3.2.1-3.2.2). The LCI data for each stage was separately modeled using LCA software, and then assessed using the life cycle impact assessment (LCIA) method. For assessing the impacts, associated LCI data, selected method and impact categories are discussed in the following sections. In this study, the contributions of waste materials generated at different stages due to the prevailing waste management practices were evaluated. The results were then compared due to the adoption of resource recovery and the CE principles. Therefore, two scenarios were considered in this study:

- Base scenario (BS): Construction waste management through off-site waste sorting system (existing system) in Hong Kong, where the inert materials are sent to public fill and non-inert materials are sent to landfill after sorting.
- Alternative scenario (AS): Waste management during construction and renovation stages through on-site waste sorting system, and demolition waste by combining on-site and off-site sorting systems (proposed system), for ensuring the maximum recovery and recycling of materials.

3.3. Assumptions and considerations

Due to the complexity of waste treatment during different building stages, several assumptions and considerations were made in this LCA study.

- During construction stage: (i) About 80% of the materials (wood and timber, plastics, paper and cardboard) recovered through on-site sorting can be recycled (for the AS); (ii) no material are recovered from off-site sorting (for the BS); and (iii) 100% of metals can be recovered for all scenarios according to Hossain et al. (2017).
- During renovation: (i) About 100% of ceramics and wood waste can be recycled (for the AS) according to Ghose et al. (2017), while other wastes are disposed of at landfill (for the AS); and (ii) all wastes are sent to landfill, except ceramics tiles which are delivered to public fill (for the BS).
- During end-of-life: (i) About 100% of concrete, metals, ceramics, wood, plastics and glass materials can be recovered, whereas the recycling efficiency of glass is 90% (Vitale et al., 2017), concrete and ceramic, reinforced steel scrap and copper are 85%, 90% and 64%, respectively from building demolition waste (Ghose et al., 2017), and plastics was assumed for 80% (for the AS); and (ii) all materials are sent to landfill, while concrete and ceramic are sent public fill, and metals are recycled with the same recycling efficiency (for the BS).

In this study, the recovery of materials is considered to be reused in producing secondary materials or products under different industrial symbiosis (Ghose et al., 2017; Hossain et al., 2017; Vitale et al., 2017).

3.4. Life cycle inventory analysis

The life cycle inventory (LCI) was performed according to the guidelines provided by ISO 14,040-44 standards (ISO, 2006a, b). In addition to collecting the first-hand inventory data (waste compositions, generation rate, etc.) during the case specific field visits in Hong Kong, different secondary data were collected from various literature (e.g. Mercante et al., 2012; Ghose et al., 2017; Hossain et al., 2017; Vitale et al., 2017). Different upstream databases (e.g. the China Light and Power (CLP), the Chinese Life Cycle Database (CLCD), European reference Life Cycle Database (ELCD) and Ecoinvent) were used as upstream data (e.g. for electricity and fuel consumption, transportation, waste landfilling, and other materials production). The details of data sources used are listed in Tables 4–6. The landfill disposal of different waste constituents was modeled separately, and the total impacts were assessed based on the waste compositions. According to the system boundary described in Fig. 3, the transportation distances were calculated from the construction sites to the processing and transformation sites, and then to the reuse or disposal sites (shown in Table 4). Based on the volume of the trucks and their carrying capacities, the transport correction factors were calculated according to Marca (2010) and Mercante et al. (2012), and can be found in Hossain et al. (2017).

3.5. Materials substitution and avoided burdens

The materials substitution and their avoided burdens (e.g. substitutional approach) was applied in this study, as this approach deals with the co-products or multi-functional processes, and includes credits for burdens that are avoided (Rigamonti et al., 2009; Brander and Wylie, 2011). This study considered different waste materials / products that can be recycled and used to replace virgin materials. Therefore, recycled materials are credited, and the credits are ultimately allocated to the corresponding processes. For instance, the BS and AS were credited due to the recycling and reuse of metal scraps, whereas the AS was credited for other materials as the potentiality of waste recovery is increased. In both of the processes, the environmental

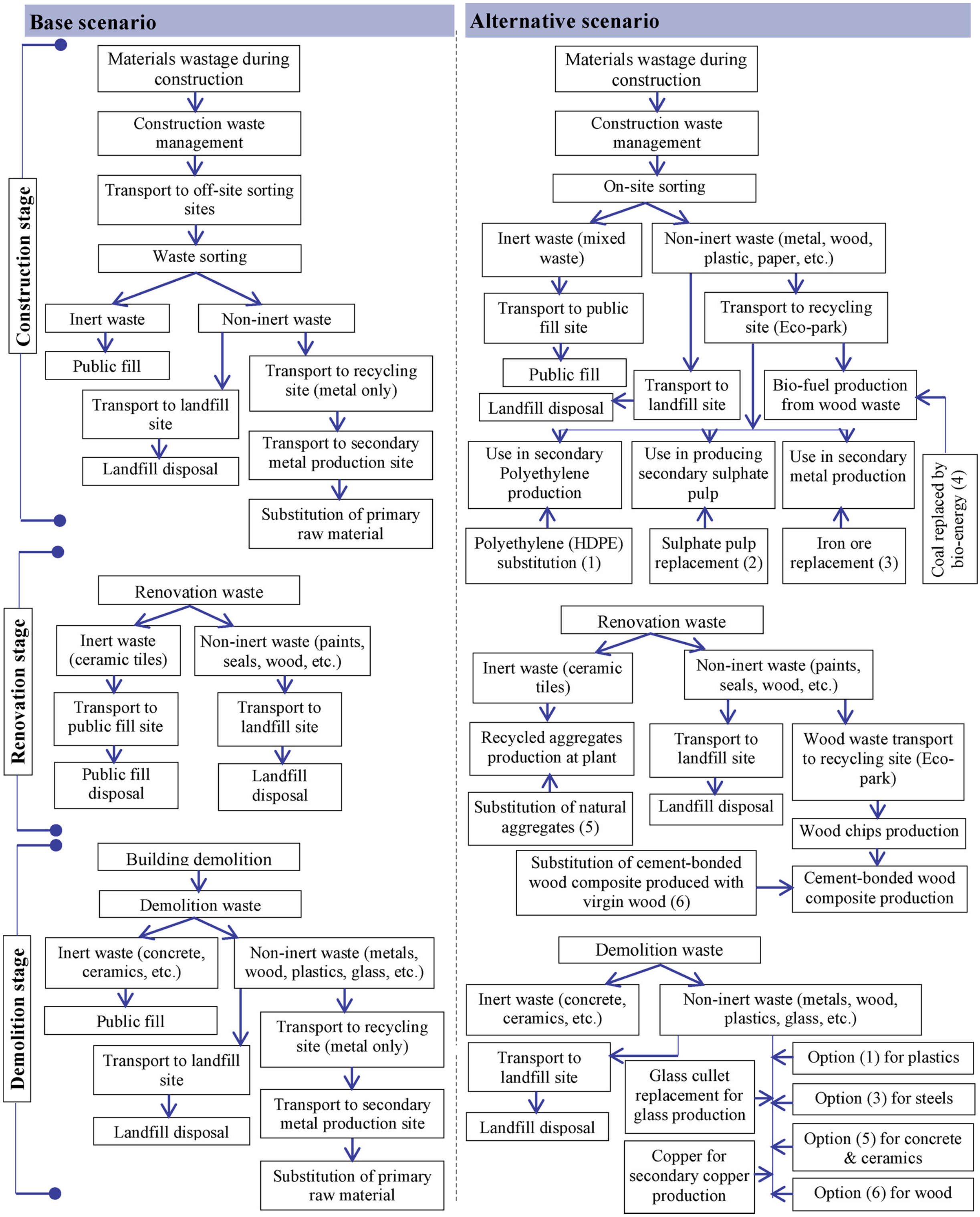


Fig. 3. System boundary and considerations adopted in this study.

impacts due to recycling and recovery, and transportations were taken into account as induced impacts, and the savings due to the substitution of virgin raw materials / products with recovered materials were considered as avoided impacts by considering the corresponding substitution ratio. Based on the materials flow shown in Tables 1–3 (at different stages), the environmental impacts (both induced and avoided) of waste materials are then allocated to per unit of building (functional unit) through the BS and AS processes. The substitution approach has been widely applied in the waste management systems (Dahlbo et al., 2015; Mastrucci et al., 2017; Ghose et al., 2017; Hossain et al., 2017; Vitale et al., 2017).

In addition, the downstream consumers of some waste materials were considered in this study based on our previous study (Hossain et al., 2017). For instance, the user (e.g. wood pellets producer) of wood and timber waste from the construction stage is available in Hong Kong, and thus the transport distance was modeled from the construction site to the wood pellet manufacturing site and also to the landfill sites (unrecovered portion). Similar assumption is used for concrete and

Table 4
Transport data of different materials.

Materials	Locations	Transport type	Distance (km)	Upstream database
Inert and mixed waste	Construction site to public fill site	Trucks (30 t)	18.0	CLCD, 2010a
Non-inert and mixed waste	Public fill site to landfill site	Trucks (30 t)	4.0	CLCD, 2010a
Non-inert waste	Construction site to landfill site	Trucks (30 t)	20.0	CLCD, 2010a
Non-inert waste	Construction site to waste recycling sites (Tuen Mun recycling facilities)	Trucks (30 t)	36.0	CLCD, 2010a
Non-inert waste	Off-site sorting facilities to recycling facilities (Tuen Mun waste recycling facilities)	Trucks (30 t)	45.0	CLCD, 2010a
Non-inert waste (metal, plastic and paper)	Recycling sites to secondary products processing sites (Tuen Mun waste recycling facilities to mainland China)	Inland barge; Trucks (30 t)	120: 30	CLCD, 2010a: CLCD, 2010d

ceramic waste (e.g. from the generation site to off-site sorting site and then public fill disposal or to recycled aggregates manufacturer for producing recycled aggregates). In Hong Kong, there is no local downstream users of all other recovered materials (e.g. metals, glass, paper and cardboard, hardwood, plastic and rubber) locally, and this study thus considered the nearest downstream users (i.e. located in southern China) and the transportation distances were modeled accordingly (Table 5).

The data and substitution ratio of bio-energy (e.g. heat) generation from wood pellets produced from recycled wood and timber waste (construction waste), and substituting coal energy for industrial use (e.g. in the cement industry) were collected from Hossain et al. (2016a). However, the recovered hardwood (e.g. doors and other woods) from renovation and demolition cannot be reused to bio-fuel production due to different chemicals (e.g. varnish, CCA-treatment, etc.). But this can be reused in producing cement-bonded wood composite, as this bonded with cement materials in the composite (Hossain et al., 2018; Hossain and Poon, 2018b). All other recovered materials and their avoided materials / products, corresponding substitution ratio, sources of data are shown in Table 6.

As shown in Tables 4–6, different literature and databases were used in this study. Given the diversity of materials (e.g. waste materials, recovered materials, avoided materials / products, etc.); energy; processes (e.g. deconstruction, sorting, recycling, landfilling, etc.); and transport systems were associated with this study, it is extremely difficult to collect the required upstream data from one source. This is even more complicated when the study is conducted in a region with severe shortage of local or regional databases. Therefore, this study attempted to use local sources (e.g. CLP which is a local power company) and literature for some processes, energy consumption and materials (Tables 5 and 6), and regional databases (e.g. CLCD) for transportation and energy consumption (Tables 4 and 5). Nonetheless, European databases (e.g. ELCD and Ecoinvent) were used for many of the processes (e.g. landfilling of different waste materials) (Table 5) and the production of avoided materials / products (Table 6).

3.6. Life cycle impacts assessment

According to the generation and compositions of waste at different building stages, the studied scenarios were modeled using the LCI data (Tables 1–6) through a LCA software – SimaPro 8.5.2™, and the environmental impacts for each scenario (per functional unit) were then assessed using the IMPACT 2002 + LCIA method. In this study, a wide range of mid-points (impact categories) and damage oriented indicators (single score) were assessed based on IMPACT 2002+ method which focused on the regional and global significance (Jolliet et al., 2003). The mid-point categories include respiratory inorganics, ozone layer depletion, acidification (both terrestrial and aquatic) potential, aquatic eutrophication potential, global warming potential, and non-renewable energy consumption. The results generated for waste materials at different stages of building through the BS were then compared with the resource recovery scenario through the AS. Finally, the contributions to the total impacts of building by the studied scenarios were analyzed.

4. Results and discussion

Based on the waste materials flow at different stages of building (Tables 1–3), LCI data (Tables 4–5), materials recovery and recycling with subsequent substitution (Table 6), and selected impacts categories with the chosen LCIA method (discussed in Section 3.6), the LCA results for both the base and alternative scenarios are described in the following sections.

4.1. Environmental profile for BS

The LCA results of the selected impact categories for considering waste generation and management at different stages of building are given in Table 7. The results show that the renovation works including the materials replacement and renovation waste treatment associated with significantly higher environmental impacts than those of the construction and end-of-life stages. Much lower impacts were associated with the end-of-life than the construction and use stages in most of the impact indicators, as the recovery of metals significantly reduces the total environmental impacts due to the prevailing demolition waste management strategies.

In the category of global warming potential, about 140 kg CO_2 eq GHG emissions was associated with the waste management during construction, renovation (including replaced materials) and demolition (including demolition itself) per m^2 of building, in which material replacement during renovation contributed to 91 kg CO_2 eq GHG emissions.

As examples, the contribution of impacts comparison in the categories of GHG emissions and non-renewable energy consumption is given in Fig. 4. It can be seen that resource recovery with the existing strategy (e.g., BS), particularly metal recovery reduces the GHG emissions and energy consumption in both the construction and end-of-life stages significantly. For instance, the induced GHG emissions was 33 and 43 kg CO_2 eq for the construction and end-of-life stages, respectively. While, the recovery of metals avoided 8 and 22 kg CO_2 eq emissions correspondingly (Fig. 4). It is noted that no impacts can be avoided for renovation with the existing strategy. Similar explanations are also applicable for other impact categories.

Thus, the environmental assessment of building without considering these factors will lead to an underestimation of the actual impacts, as well as misleading the accuracy of the assessment. However, many previous studies have focused on the impacts assessment, particularly in terms of carbon emitted from buildings without critically considering the factors just mentioned (Dong and Ng, 2015; Hong et al., 2015; Gan et al., 2017).

4.2. Environmental impacts for AS

When the resource recovery principle is adopted through the AS, higher savings of environmental impacts are observed, especially due to

Table 5
Energy requirements for sorting and recycling of waste materials.

Management practices	Materials	Activity	Energy requirements	Sources of data	Upstream database
On-site sorting (construction and renovation waste)	Wood and timber, steel scrap and metals, plastic and rubber, and paper and cardboard, tiles and hardwood	On-site waste sorting manually in separate bins, containers and designated locations	Negligible	Field visits	–
Building demolition	–	Included all demolition activities	85 MJ/m^2	Hong et al. (2017)	CLP, 2014; CLCD, 2010b,c
On-site sorting (demolition waste)	Hardwood doors, Copper, glass, etc.	Separate bins, containers and designated locations	Included into the building demolition	–	–
Off-site sorting	Inert (concrete, ceramics), metals and other non-inert (plastics)	Off-site sorting manually and mechanically (screening and on-site handling)	5 MJ/t (electricity) & 11 MJ/t (diesel)	Mercante et al. (2012)	CLP, 2014; CLCD, 2010b,c
Public fills	Inert waste (concrete and ceramics)	Processing and disposal in public fill site	Refers to database	Inert waste landfill	Ecoinvent, 2013a
Landfills	Non-inert waste (wood waste)	Processing and disposal in landfill site	Refers to database	Wood waste landfill	Ecoinvent, 2013b
	Non-inert waste (plastic waste)	Processing and disposal in landfill site	Refers to database	Plastic waste landfill	Ecoinvent, 2013c
	Non-inert waste (paper and cardboard)	Processing and disposal in landfill site	Refers to database	Paper waste landfill	Ecoinvent, 2013d
	Non-inert waste (glass waste)	Processing and disposal in landfill site	Refers to database	Glass landfill	ELCD, 2013
	Non-inert waste (sealing materials)	Processing and disposal in landfill site	Refers to database	Mixed waste disposal	Ecoinvent, 2013j
	Non-inert waste (paint materials)	Processing and disposal in landfill site	Refers to database	Waste paint landfill	Ecoinvent, 2013i
	Scrap steel	Treatment into disposal in landfill site	Refers to database		Ecoinvent, 2013n

the recovery of secondary materials from the construction and end-of-life stages. The results of the selected impact categories for the AS are shown in Table 8. Similar to the BS, the renovation works associated with significantly higher environmental impacts than those of the construction and end-of-life stages. Negative values were found for most of the categories at the mentioned stages as the avoided impacts were much higher than the induced impacts. Due to the potential replacement of different primary materials / products by the recovered materials, much potential savings were associated with both of the construction and end-of-life stages in most of the impact indicators.

For example, about 147 and 62 kg CO_2 eq GHG emissions can be potentially avoided through the construction and end-of-life stages, respectively, while about 91 kg CO_2 eq was induced due to renovation works for per m^2 of building that makes the total potential saving of 118 kg CO_2 eq GHG emissions. Similarly, about 1.65 GJ of non-renewable energy consumption can be potentially saved for adopting the resource recovery principle through the AS.

4.3. Comparative contribution analysis

As an example, the contribution of different processes to the total GHG emissions at different stages for both scenarios are shown in Fig. 5. At the construction stage, the recovery of steel and iron scrap (and substitute of iron ore) avoided 7.86 kg CO_2 eq GHG emissions, whereas about 4.45, 1.45, 4.82, 20 and 1.94 kg CO_2 eq GHG emissions were induced for mixed waste transport to off-site sorting site, waste sorting, inert waste public filling, non-inert waste transport and landfilling, and recovered materials transport to use site, respectively for the BS. For the AS through the on-site sorting, about 6.49, 14.58 and 21.29 kg CO_2 eq were induced for inert waste transport and public filling, non-inert waste transport and landfilling, and recovered materials transport to recycling sites and then to utilization sites, respectively. However, about 190 kg CO_2 eq can be potentially saved for this approach due to resources recovery and substitute secondary materials, in which about 88% saving were observed by replacing coal energy (heat) with the bioenergy generated from wood pellets produced from the wood waste generated at construction sites, 4% due to the substitution of iron ore by scrap metal and steel, 6% for polyethylene production from secondary plastics, and 2% for sulphate pulp production from recovered cardboard and paper.

During the renovation stage, the impacts were almost similar for both the BS and AS, as only a portion of inert waste materials can be potentially recovered. In addition, more than 95% of the impacts were induced due to the material replacement for renovation works.

At the end-of-life stage, about 42.80 kg CO_2 eq GHG emissions was associated with the management for different processes through the existing practice (BS), while 21.70 kg CO_2 eq was avoided due to the recovery of secondary metals and replacement of iron ore and copper production. After deducting the avoided impacts, the processes contribute to 21 kg CO_2 eq emissions to per m^2 of building. However, about 21.4 kg CO_2 eq was induced for different processes, and avoided 82.93 kg CO_2 eq emissions for recovered materials for the AS. In saving, about 38% was from producing recycled aggregates from concrete waste (that replaces virgin aggregates), 25% from iron ore (substituted by steel and iron scrap), 34% from polyethylene (substituted by recovered plastics), 2% from glass and 1% from copper (Fig. 5). The materials cycling at this stage contributes to -62 kg CO_2 eq emissions from per m^2 of building.

4.4. Comparative environmental evaluation for BS and AS

Comparative evaluation of the selected environmental impacts indicators at different stages for both scenarios are shown in Fig. 6. The results show that the BS had a much higher impact than the AS in the category of respiratory inorganics. As all the processes at different stages for the BS are associated with 0.86 kg PM2.5 eq emissions which

Table 6
Substitution of secondary materials obtained in recycling and associated avoided impacts.

Recovered material / product	Avoided product / material	Substitution/ replacement ratio	Sources of data	Upstream reference / database
Bio-energy from wood and timber (generated at construction activities)	Energy (heat from coal)	1: 0.81	Hossain et al. (2016a)	Ecoinvent (2013e)
Metals	Iron ore	1: 1.40	WSA (2016)	Ecoinvent (2013f)
Plastics	Polyethylene (HDPE)	1: 0.81	Mercante et al. (2012)	Ecoinvent, 2013g
Paper and cardboard	Sulphate pulp	1: 0.83	Mercante et al. (2012)	(Ecoinvent, 2013h)
Copper scrap	Copper	1:1	Ghose et al. (2017)	(Ecoinvent, 2013l)
Glass	Glass cullet	1:1	Ghose et al. (2017)	(Ecoinvent, 2013m)
Concrete and ceramic tiles	Natural aggregates	1:1	Ghose et al. (2017); Hossain et al. (2016b)	Hossain et al. (2016b)
Hardwood (from renovation and demolition)	Cement-bonded wood composite	1:1	Hossain et al. (2018)	Ecoinvent (2013k)

was 28% higher than the AS (0.66 kg PM2.5 eq) for per m^2 of building. Similarly, about 25% lower impact in the category of ozone layer depletion was found in the AS than in the BS. In the AS, significant impacts could be avoided due to material recovery from the end-of-life stage.

In the category of acidification potential, it was found that the BS is associated with very high acidification impacts (about 2.97 kg SO_2 eq). However, about 1.83 kg SO_2 eq acidification impacts could be avoided for the AS due to resources recovery and their subsequent valorization to produce various secondary materials / products. Similarly, about 84% lower aquatic eutrophication impacts were found for the BS than those of the AS. In this category, the highest contribution was mainly due to the existing management strategy (inert to public fills and non-inert materials to landfills, and only metals to recovery) at the end-of-life of building (Fig. 6).

For global warming potential, it is also estimated that about 140 kg CO_2 eq GHG emissions was associated with the BS. However, for the AS, about 118 kg CO_2 eq GHG emissions could be avoided due to potential of higher amount of materials recovery mainly the construction and end-of-life stages. Although much higher amount of material recycling is potentially available at the end-of-life stage, higher GHGs saving was observed in the construction stage. This is because a higher amount of timber waste was generated at this stage, and thus has a higher potential for reused in producing bio-fuel and substituting coal energy (Fig. 5).

By including all the three stages, about 1892 MJ non-renewable energy was consumed for the BS, whereas a significant amount of non-renewable energy (about 1650 MJ) can be avoided for the AS due to a higher amount of recyclable materials generated during the construction and end-of-life stages, and thus a highly potential to recover and subsequent saving.

Based on the selected impact indicators, the net environmental burden was assessed according to the IMPACT 2002+ method (shown in Fig. 7). The net environmental burden (also called the eco-point) is a dimensionless figure, measured in units of milli-points (mPt), which indicates the potential number of people being affected by the environmental impacts in a period of one year. The eco-point is calculated based on the standardization factors given in the mentioned method (Jolliet et al., 2003). The figure shows that renovation works including the material replacement contributed significantly higher net environmental impacts for both the BS and AS. For the BS, the eco-point was estimated to be 111.9 mPt/m^2 of building which is about 63% higher than that of the AS. For the AS, the induced eco-point was 108 mPt due to renovation works, while about 37 mPt and 29 mPt could be avoided due to material recovery and utilizations at the construction and end-of-life stages, respectively. The LCA results demonstrated that significant net environmental impacts could be avoided when waste management (i.e. generated during the construction, renovation and end-of-life stages of building) through practicing the AS in Hong Kong.

Similar trends were also observed in previous studies. For instance, about 77% reduction of climate change impacts were reported compared to conventional disposal of waste materials for per m^2 of building (associated with materials and end-of-life only) due to reuse and recycling of materials by Coelho and de Brito (2012). The global warming potential (GWP) impact reduction was about 350 kg CO_2 eq/t of C&D waste management in Finland due to the recovery and recycling of materials such as timber, metals and concrete (Dahlbo et al., 2015). Similar results were also found for C&D waste management systems through different sorting systems and resource recovery by Mercante ; et al;. (2012) and Hossain et al. (2017).

About 33 kg CO_2 eq GHG emissions was associated with waste management at construction stage through the BS, whereas about 148 kg CO_2 eq GHG emissions can potentially be saved through the AS (per m^2 of building). The values were supported by previous study (Hossain et al., 2017). During the use phase, the renovation works associated with about 94 kg CO_2 eq GHGs/m^2 in this study which was considerably higher when compared to 45 kg CO_2 eq GHGs/m^2 reported by Ortiz-Rodríguez et al. (2010) and 38 kg CO_2 eq GHGs/m^2 reported by Kumanayake and Luo (2018). At the end-of-life stage, about 21.1 CO_2 eq GHGs/m^2 was associated for the BS which was consistent with other studies. For example, about 25.17 eq GHGs/m^2 and 18 CO_2 eq GHGs/m^2 were found for similar type of building in South Korea by Roh and Tae (2017) and in China by Guo et al. (2017), respectively. However, about 49 CO_2 eq GHGs/m^2 can be potentially reduced due to

Table 7
Contribution to the total environmental impacts.

Selected impacts categories (per m^2)	Construction stage	Use stage		End-of-life stage		Total
	Construction WM	*Materials replacement*	*Renovation WM*	*Demolition*	*Demolition WM*	
Respiratory inorganics (kg PM2.5 eq)	−0.00704	0.91354	0.00289	0.00815	−0.05522	0.86232
Ozone layer depletion (kg CFC-11 eq)	4.25E-07	7.89E-06	8.30E-08	1.53E-08	−1.90E-07	8.22E-06
Acidification potential (kg SO_2 eq)	0.36	2.52	0.12	0.12	−0.16	2.97
Aquatic eutrophication (kg PO_4 P-lim)	0.11875	0.03237	0.02355	2.25E-05	0.45981	0.63450
Global warming (kg CO_2 eq)	25	91	3	4	17	140
Non-renewable energy (MJ eq)	252	1258	39	85	259	1892

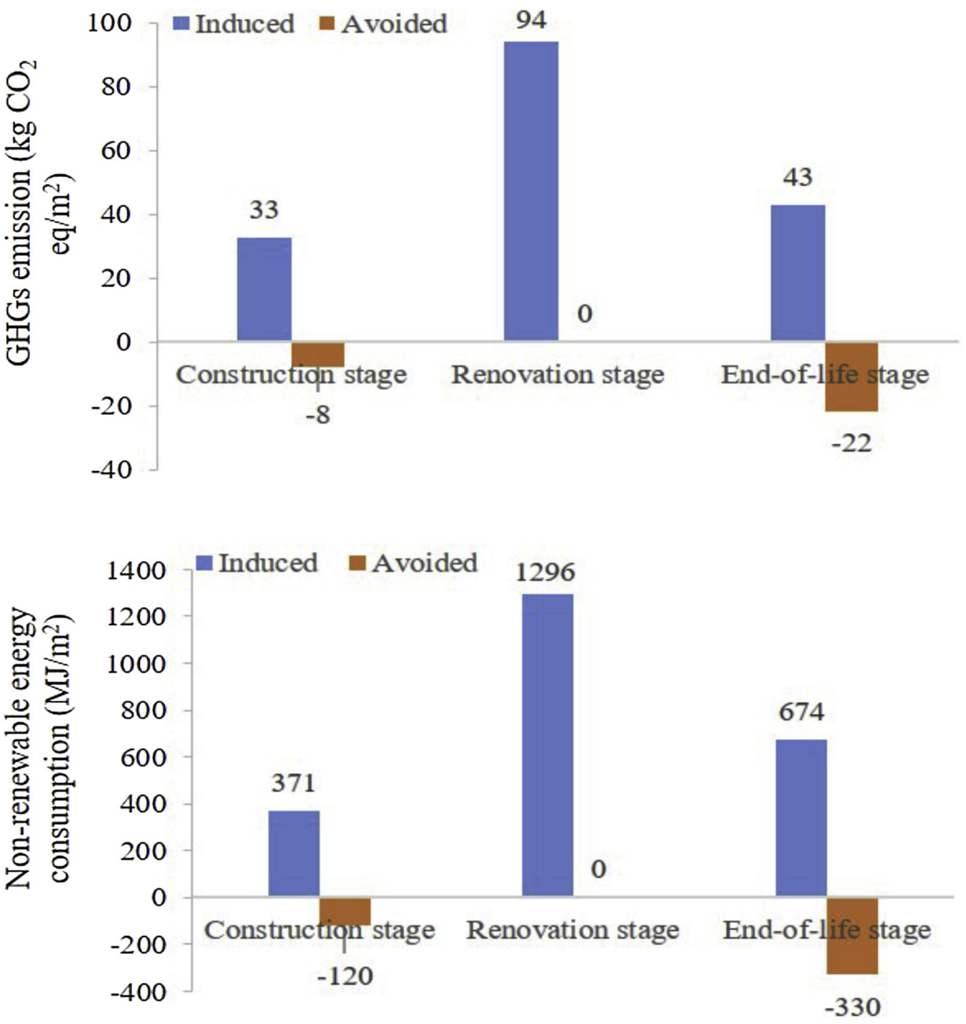


Fig. 4. Comparison of impacts contribution at different stages for BS.

Table 8
Environmental impacts for adopting resource principle.

Selected impacts categories (per m^2)	Construction stage	Renovation stage	End-of-life stage	Total
Respiratory inorganics (kg PM2.5 eq)	−0.14275	0.91533	−0.11539	0.65719
Ozone layer depletion (kg CFC-11 eq)	7.62E-08	7.89E-06	−1.80E-06	6.17E-06
Acidification potential (kg SO_2 eq)	−2.38	2.57	−2.02	−1.83
Aquatic eutrophication (kg PO_4 P-lim)	0.08329	0.03239	−0.01423	0.10145
Global warming (kg CO_2 eq)	−148	91	−62	−118
Non-renewable energy (MJ eq)	−1220	1256	−1686	−1649

the adoption of resource recovery principle in this study (Fig. 5). The value was also consistent as 67 CO_2 eq GHGs/m^2 reduction for end-of-life waste recovery reported by Cuéllar-Franca and Azapagic (2012).

4.5. *Influence on the buildings' environmental impacts*

This study also assessed the influences of waste management during the construction, use (renovation works including the replacement materials) and end-of-life stages on building's environmental impacts. It is noted that comprehensive studies (e.g. cradle-to-grave with wide range of environmental impact indicators) on assessing the environmental impacts of building are still lacking in Hong Kong. However, a few studies were available which primarily focused on assessing the carbon emissions per m^2 of building construction (using a cradle-to-site system boundary) in Hong Kong (with the system boundary definition based on EN 15,978: Sustainability of Construction Works – Assessment of Environmental Performance of Buildings, as well as that described by Rasmussen et al. (2018)). However, none of them have considered the GHG emissions due to waste management generated at construction site into their assessment. For example, the GHG emissions of residential building construction was reported by Dong and Ng (2015) as 637 kg CO_2 eq/m^2, Gan et al. (2017) as 497 kg CO_2 eq/m^2, and Ng and Kwok (2013) as 560 kg CO_2 eq/m^2. Therefore, the influence on GHG emissions to the total emissions of building by the considered aspects was evaluated and shown in Fig. 8. It is also noted that GHG emissions due to operation was not considered in this study, as the studied aspects have no or little influence on the energy consumption and subsequent emissions due to the operation of building.

It can be seen that the average GHG emissions of residential building considered in Hong Kong was 565 kg CO_2 eq/m^2. However, based on the collected data and assumption made in this study, the results show that about 25, 94 and 21 kg CO_2 eq/m^2 of GHG emissions

Fig. 5. Process contributions of total GHG emissions for BS and AS.

were contributed by the existing waste management (through the BS) from the construction stage, renovation works (including the material replacement), and the end-of-life stage, respectively. The total GHG emissions could be 705 kg CO_2 eq/m^2, indicating about 20% underestimation of the existing studies for not considering the aspects included in this study. However, GHG emissions could be 446 kg CO_2 eq/m^2 should the proposed strategies of the AS be adopted, indicating 37% potential reduction due to the adoption of resource recovery principle and material recycling to produce secondary materials and energy (details are already presented in Table 8, Figs. 5 and 6).

Due to the complex system and long-time span of building, different assumptions and considerations were taken into account in this study (mentioned in Section 3.3). Thus, many of them, especially the recovery rate and the use of technology may vary. In addition, the energy consumption for different systems, e.g. the recovery process and fuel mix of electricity may also differ. Therefore, the results presented in this study are mainly based on the present scenarios. Thus, sensitivity analysis using a dynamic LCA is recommended for further studies. In addition, statistical analysis of information could improve the quality of the findings. However, statistical analysis is difficult with the data used in this study, as the data was collected from a typical building (i.e. first hand data) or average (i.e. from literature). Thus, this aspect should be considered in the future study. Moreover, the use of mixed sources or different databases can hinder the reliability of the findings as a specific database may better represent a specific local or regional condition. Due to the lack of local / regional databases for the associated huge volume of materials and processes, this study used different sources including local and regional databases, literature, and the European databases. Although this is a major limitation of this study as it may affect the accuracy of the findings, this cannot be avoided at present. Therefore, it is suggested to develop local / regional databases in the near future for better representation and improved accuracy of the results.

5. Conclusions

Comprehensiveness including the material flow and waste disposal is lacking in many building environmental research. By addressing the identified factors, i.e. contribution of waste materials to environmental impacts of building at various stages, this study critically examined the influence of building environmental impacts through existing strategy (BS) and the proposed material recovery principle (AS). For BS, the results revealed that renovation works (including materials replacement and associated waste treatment) could lead to significantly higher environmental impacts in most of the impact indicators than those pertinent to the construction and end-of-life stages. Similar results were also observed for AS. However, higher savings were observed due to the recovery of secondary materials from the construction and end-of-life stages. Although higher amount of material recycling is potentially available at the end-of-life stage, higher saving was observed during the construction stage as significant amount of timber waste was generated at this stage (and thus a higher potential for being reused in bio-fuel production). The overall results demonstrated that by adopting the proposed material recovery principle (AS) 63% of the total impacts can be reduced compared with the BS strategy for waste treatment generated at different building stages.

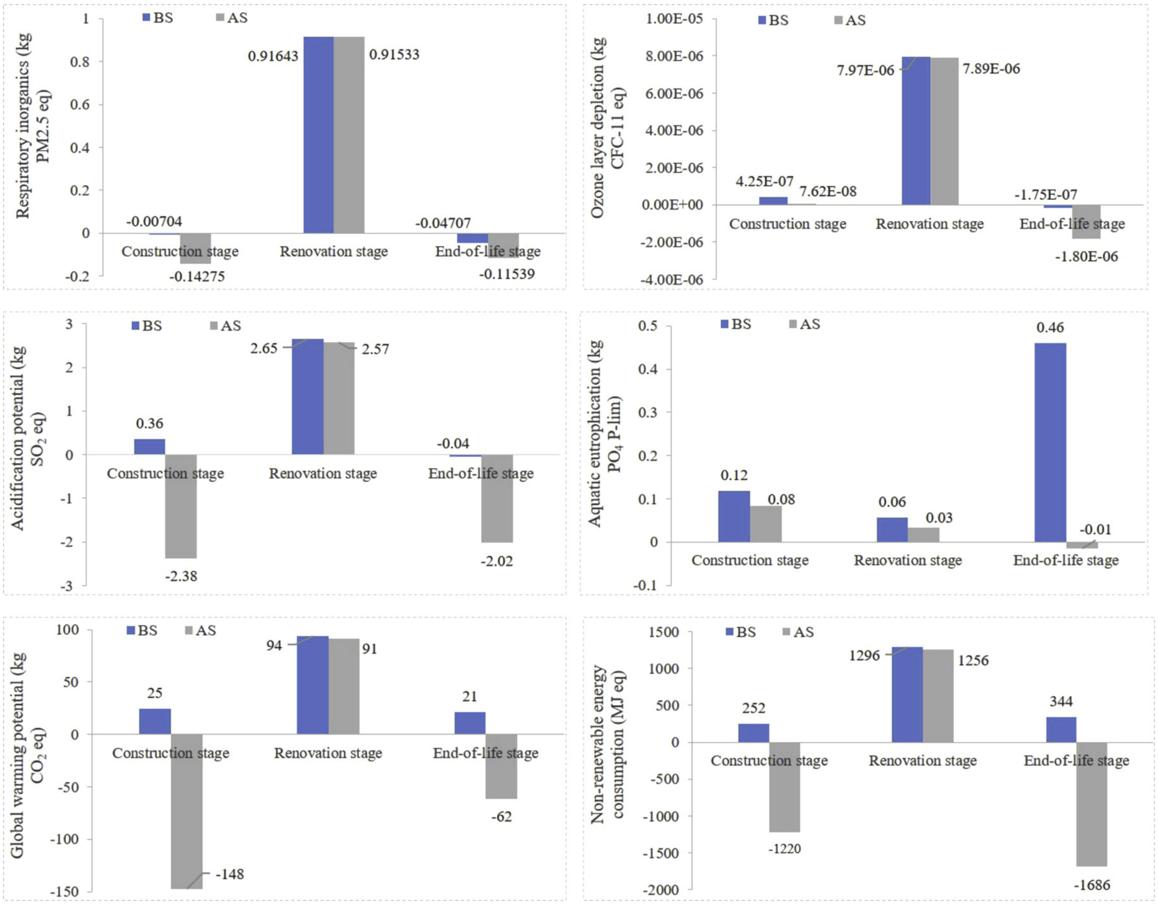


Fig. 6. Comparison and process contributions environmental impacts for BS and AS.

The results also illustrated that waste management during the construction, use and end-of-life stages can greatly influence the environmental impacts of building. Therefore, failing to consider those factors in building assessment may mislead the results and undermine the assessment accuracy. For example, a 20% under estimation of GHGs in buildings was observed for the existing strategy in Hong Kong (compared to the average GHG emissions of residential building when the factors mentioned were not considered into the assessment). Adopting the resource recovery principle for waste treatment at different building stages can substantially save primary resources, environmental impacts and minimize waste disposal problem. For instance, about 37% of the total GHGs can potentially be saved by adopting the proposed resource recovery principle when the factors mentioned were considered into the assessment.

As building construction is shifting from a linear to circular paradigm, the consideration of those factors is essential for ensuring waste reduction, resource recovery and resource-efficient construction, as well as for adopting the CE principle in the building industry. The information and findings presented in this study can significantly contribute to CE, resource recovery and building LCA research, especially

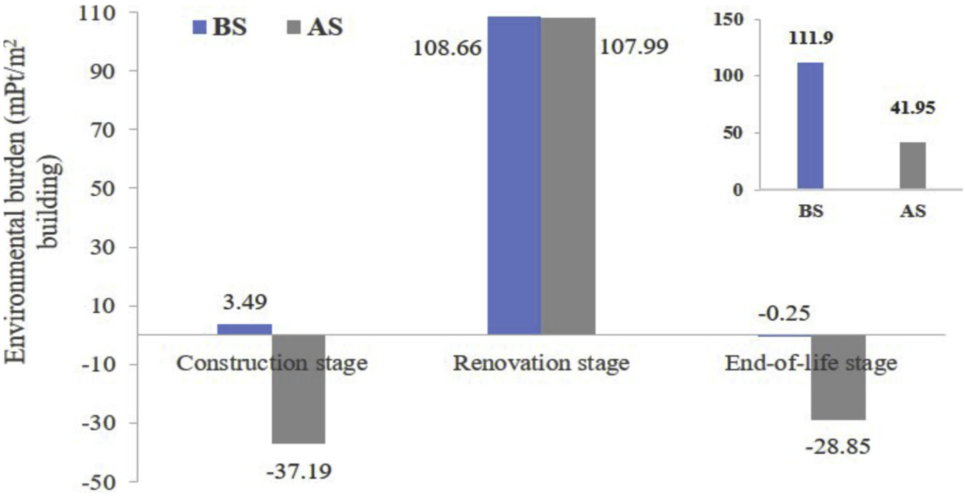


Fig. 7. Comparison of total environmental burden for BS and AS.

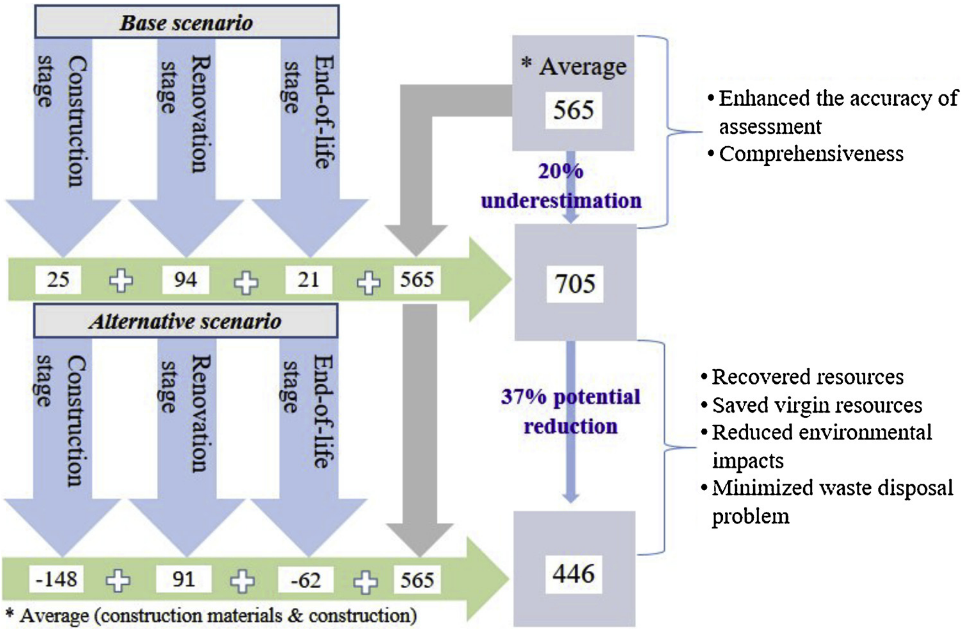


Fig. 8. Comparison of GHG emissions (kg CO_2 eq/m^2) of building for different considerations.

the way of assessment, different considerations, and influence of waste materials on the environmental impacts of building. Due to consideration of different uncertainties over the long life of building, uncertainty analysis with dynamic LCA for different scenarios would be helpful in comprehensive assessment. In addition, the shortcomings highlighted in this study should be addressed when adopting the resource recovery and CE principles in building environmental research in future.

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