Int J Life Cycle Assess (2018) 23:1654–1674
DOI 10.1007/s11367-017-1373-0

SOCIETAL LCA

Development of social sustainability assessment method and a comparative case study on assessing recycled construction materials

Md. Uzzal Hossain[1] **· Chi Sun Poon**[1] **· Ya Hong Dong**[2] **· Irene M. C. Lo**[3] **· Jack C. P. Cheng**[3]

Received: 21 May 2016 / Accepted: 7 July 2017 / Published online: 1 August 2017

Abstract
Purpose Sustainability analysis should include the assessment of the environmental, social, and economic impacts throughout the life cycle of a product. However, the social sustainability performance assessment is seldom carried out during materials selection due to its complex nature and the lack of a social life cycle assessment tool. This study presents a single score-based social life cycle assessment methodology, namely social sustainability grading model, for assessing and comparing the social sustainability performance of construction materials using a case study on recycled and natural construction materials.
Methods The proposed method is developed based on the methodological framework provided by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry guidelines published in 2009 and the methodological sheets published in 2013, the indicators and sustainability reporting guidelines provided by the Global Reporting Initiatives and ISO 26000 for social responsibility of products, and the indicators provided by the Hong Kong Business Environment Council Limited for construction sustainability. A twofold research approach is proposed in this model: the first one is the qualitative research based on expert interviews to identify, select, and prioritize the relevant subcategories and indicators, and the second one is the operational research based on the case-specific survey to collect the required data. A social sustainability index was proposed for the interpretation of the results effectively. A case study on construction materials was conducted to illustrate the implementation of the method using case-specific first-hand data.
Results and discussion The major outcome of this study is the systematic development of a social sustainability assessment tool based on the established standards and guidelines. The case study showed that four subcategories are crucial social concerns for construction materials (i.e., health and safety issues of the materials, health and safety of workers, company's commitment to sustainability, and company's policies on energy and water consumption). Based on the sustainability index proposed, using recycled aggregates from locally generated waste materials scored higher (about 31–34%) social sustainability than using imported natural aggregates. In addition, recycled aggregates and natural aggregates achieved "sustainable" and "neutral" rating sustainability levels, respectively. However, several subcategories (e.g., health and safety, working hour, forced work, training and social benefits of workers, and quality of the materials and information disclosing to public) are still needed to improve the social sustainability performance of recycled aggregates.
Conclusions An integrated social life cycle assessment method is presented in this study for assessing the social sustainability of construction materials. In addition, the reported case study in this paper is one of the first attempts for social sustainability assessment of recycled construction materials, and the method can be applied to other recycled materials/products

Responsible editor: Marzia Traverso

Electronic supplementary material The online version of this article (doi:10.1007/s11367-017-1373-0) contains supplementary material, which is available to authorized users.

✉ Chi Sun Poon
cecspoon@polyu.edu.hk

[1] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

[2] Faculty of Science and Technology, The Technological and Higher Education Institute of Hong Kong, Tsing Yi, Hong Kong

[3] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

for comparative analysis. However, several critical factors, such as integration in other life cycle methods and software, sensitivity analysis, and more case studies, are still needed for further improvement of the developed method.

Keywords Construction materials · Recycled materials · Social life cycle assessment · SSG model

1 Introduction

1.1 Background

A sustainability assessment of a product usually considers three dimensions, viz. environment, economy, and society. In the realm of life cycle assessment (LCA), there are three interactive and iterative methods, namely the environmental LCA, the life cycle costing (LCC), and the social life cycle assessment (S-LCA). As a method to assess the environmental impacts throughout a product's life cycle, the environmental LCA has already been developed and reached to its standardized form in terms of methodology, evaluation, and implementation (ISO 2006a). LCC for assessing economic perspectives also has evolved to a relatively mature stage in terms of methodology (Hunkeler 2006; Swarr et al. 2011). However, the use of the S-LCA method (Macombe et al. 2011; do Carmo et al. 2017a) for social sustainability assessment is still under rapid development (Dong and Ng 2015; Grubert 2016; Lehmann et al. 2013). Increasing scientific efforts have been devoted in S-LCA in terms of method development and case studies with wide applications after publishing "the methodological sheets for subcategories in social life cycle assessment (SLCA)" by UNEP/SETAC in 2013 and scientific meetings afterward (e.g., the SETAC Europe 24th Annual Meeting in Basel and the 4th International Seminar on SLCA in Montpellier) (Petti et al. 2016).

S-LCA 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). While S-LCA is a promising method, the collection of valid data is always a challenging issue (Kruse et al. 2009) which would restrict the implementation of S-LCA (Traverso et al. 2013). In addition, S-LCA results are fairly complex and thus difficult to be understood by decision makers (Traverso et al. 2013). Social conditions are usually dynamic and the changes of social data are much faster than environmental data, which renders even more complexity of S-LCA (Wu et al. 2014).

S-LCA is defined as "a social impact (and potential impacts) assessment method 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 (namely workers/employees, local community, society, consumers, and value chain actors) with six impact categories (namely human rights, working conditions, health and safety, cultural heritage, governance, and socioeconomic 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. UNEP/SETAC (2009) proposed a list of subcategories for conducting S-LCA, such as working hours, fair salary, child labor, health and safety, technology development, contribution to economic development, public commitment to sustainability issues, etc. (see Table 1). 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 subcategories. For instance, the creation of permanent positions is an indicator of subcategory of local employment, while working hours per week is an indicator of subcategory of working hours.

1.2 Past S-LCA studies

As a promising tool, S-LCA has undergone rapid development in terms of methodology improvement with case studies. However, several issues, such as selection of social indicators, system boundaries, functional units, data collection and availabilities, impact assessment, and results interpretations, are the main challenges for developing and conducting S-LCA (Finkbeiner et al. 2010).

In S-LCA, social impacts can be quantified using indicators across the entire life cycle of products. However, different from environmental LCA, quantification of impacts in S-LCA is currently a thorny issue. Some of the impacts (e.g., working hours) can be quantified directly, but others (e.g., culture heritage) are difficult to be assessed; consequently, meaningful conclusions are hard to be drawn (Hauschild et al. 2008; Clift 2014). This is also reflected by the difficulties in selecting indicators and converting collected data according to function units (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). Recently, Feschet et al. (2013)

Table 1 Examples of some proposed S-LCA approaches and subcategories

Author(s)		UNEP/SETAC (2009)	Hunkeler (2006)	Kruse et al. (2009)	Jørgensen et al. (2010)	Ciroth and Franze (2011)	Benoît-Norris et al. (2012)	Arcese et al. (2013)
Studied case		General S-LCA method	Detergent production	Salmon production	Validity in S-LCA	Laptop computer	Supply chain of products	Tourism
Methodology		S-LCA guidelines	Mid-point based S-LCA	Combined top-down and bottom-up approach	Proposed validation method	UNEP/SETAC proposed methodology	The Social Hotspots Database	Social accounting and business management tools
Number of category		5				5	5	3
Subcategories	Freedom of association and collective Bargaining	√		√		√	√	
	Child labor	√			√	√	√	
	Fair salary	√		√		√	√	√
	Working hours	√	√	√		√	√	√
	Forced labor	√		√		√	√	
	Equal opportunities/discrimination	√		√		√	√	
	Health and safety (worker)	√				√	√	√
	Social benefits/social security	√				√		√
	Health and safety	√				√		
	Feedback mechanism	√				√		√
	Consumer privacy	√				√		√
	Transparency	√				√		√
	End of life responsibility	√				√		
	Access to material resources	√				√		√
	Access to immaterial resources	√				√		√
	Delocalization and migration	√				√		√
	Cultural heritage	√				√		√
	Safe and healthy living conditions	√				√		√
	Respect of indigenous rights	√				√	√	√
	Community engagement	√				√		√
	Local employment	√				√		√
	Secure living conditions	√				√		√
	Public commitments to sustainability issues	√				√		
	Contribution to economic development	√				√		
	Prevention and mitigation of armed conflicts	√				√	√	
	Technology development	√				√		
	Corruption	√				√		
	Fair competition	√				√		
	Promoting social responsibility	√				√		
	Supplier relationships	√				√		
	Respect of intellectual property rights	√				√		

Table 1 (continued)

	Use stage responsibility[a,b] Product service and labeling[a,b] User satisfaction[a,b] Training and education[a,b] Public opinion on materials[b,c] Support from the government[b,c] Materials (use and practice)[a,b,d] Energy and water consumption (reduction strategies)[a,b,c] Emissions (reduction strategies)[a,b,c] Solid waste and effluent (strategies for management)[a,b,c] Biodiversity (effects on local biodiversity) [a,b,d,e]						
Author(s)	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	Laptop computer	Not specified	Steel and cement	Bio-energy value chains	Citrus farming	Building construction project	Construction materials
Methodology	Guidelines given by Benoit-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	2	5	3	3	3	6
Subcategories	√		√			√	
	√	√	√			√	√
	√		√	√		√	√
	√					√	√
	√		√			√	√
	√	√	√	√	√	√	√
	√	√	√		√	√	√
	√			√			√
	√		√				√
	√						
	√						
	√						
	√						√
	√		√			√	√
	√				√		√

Table 1 (continued)

√						
√		√			√	
√		√			√	√
√						
√					√	√
√		√			√	√
√						√
√					√	√
√		√	√	√		√
√			√			
√		√				√
√	√					
√		√	√			√
√						√
√		√				√
√						√
						√
						√
						√
						√
						√
						√
			√	√		√
						√
						√
						√
						√

[a] GRI (2013)
[b] Developed in this study based on the mentioned references
[c] BECL (2013)
[d] De Luca et al. (2015)
[e] Henke and Theuvsen (2014)

attempted to establish a cause-effect chain in S-LCA by considering the economic activity of a product chain and the health status of the population in the country. Bocoum et al. (2015) developed impact assessment relationship in S-LCA by allowing a comparison of socioeconomic impacts linked to various important changes in the production stage of life cycles. In terms of methodology development, characterization and weighting for qualitative indicators are challenging topics (Hosseinijou et al. 2014; do Carmo et al. 2017b). Furthermore, a methodological framework of S-LCA is still at an early stage of development (Haaster et al. 2017). Therefore, more fundamental scientific effort is needed.

In the past, several review studies were published. A review of S-LCA application on wood-based production system was conducted in Germany by Siebert et al. (2016). Macombe et al. (2013) reviewed the possibilities and development needs of S-LCA in biodiesel production at the three different levels (e.g., company, regional, and state level). Chhipi-Shrestha et al. (2015) critically reviewed the methodologies for impacts assessment applied in S-LCA and established the current development by highlighting areas for improvement. Petti et al. (2016) systematically reviewed the applications of S-LCA method in different case studies by highlighting the hot spots and weaknesses of the application of the S-LCA. In addition, several systematic reviews were conducted on the application of the S-LCA theory and implications (e.g., Petti et al. 2014; Di Cesare et al. 2014, 2016; Grubert 2016). From the broad topics of S-LCA theory and applications, some of the past representative S-LCA studies are listed in Table 1. The studies were selected based on the multiplicity of studied cases (e.g., energy, fisheries, agriculture, construction, tourism and electronics sectors, and various products), methodologies (e.g., top-down approach, mid-point based, scaling approach, multicriteria decision-making approach, life cycle sustainability, etc. for impact assessment), and evaluated stakeholder categories and subcategories (e.g., UNEP/SEATC guidelines, Global Reporting Initiatives, etc.). Some of the studies adopted the method given in the UNEP/SETAC guidelines (UNEP/SETAC 2009). For instance, Arcese et al. (2013) developed a management tool for the tourism sector based on the UNEP/SETAC guidelines and evaluated the negative and positive social impacts. Valdivia et al. (2013) concluded that the guidelines provided by UNEP/SETAC (2009) could help in easing the overall development efforts in performing S-LCA, and it revealed that data acquisition was a key issue of a S-LCA study. 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 and value chain actors). Martínez-Blanco et al. (2014) conducted a case study on two mineral fertilizers and an industrial compost in line with the UNEP/SETAC S-LCA guidelines, whereas the social hotspots database (SHDB) was adopted for the secondary processes. Ramirez et al. (2014) proposed a S-LCA method based on UNEP/SETAC guidelines and developed a set of methodological sheets for calculating the impacts at the subcategory level. Reveret et al. (2015) assessed the socioeconomic impacts of milk production in Canada using the UNEP/SETAC guidelines. Sousa-Zomer and Miguel (2015) evaluated the applicability of S-LCA method to assess the social impacts of product-service systems using the UNEP/SETAC guidelines, and found that only a few indicators can be applied for comparative analysis of the systems.

Other studies were intended to develop new methods for S-LCA. Traverso et al. (2013) proposed a dashboard containing graphical representation of the life cycle sustainability results. Hosseinijou et al. (2014) used project data for conducting S-LCA for cement and steel. Dong and Ng (2015) conducted S-LCA on building construction processes using both national level and project specific data and developed a set of functional work sheets to calculate a single score. A few past studies also revealed the existing challenges in S-LCA. For example, Ekener-Petersen and Moberg (2013) found some major challenging issues, including result representations, identification of relevant indicators, data availabilities, impact subcategories, and functional variables. In summary, S-LCA is a continuous developing method and the available studies have covered a wide spectrum of products (Di Cesare et al. 2016), and more scientific rigor in some areas such as data collection, impact assessment, allocation methods, incorporation of values and cultural context, etc. is needed as methodological development with case studies continues in S-LCA studies (Grubert 2016). However, a standardized methodology of S-LCA is lacking and further research is required to facilitate the implementation of S-LCA in decision-making.

Based on the above literature review, the application of S-LCA of recycled construction materials cannot be found. While the importance of assessing social impacts was highlighted in the context of life cycle sustainability assessment of recycled construction materials in some past studies (Bozhilova-Kisheva and Olsen 2011), the details of methodology development (and impact assessment) and case study have not been conducted. The lack of agreement in several critical steps, such as the selection of different stakeholder categories, impact subcategories, indicators, and weighting methods, has limited the implementation of S-LCA for the assessment of sustainability of recycled construction materials. This is mainly due to the complexity of S-LCA, in particular the necessities to involve various stakeholders during the life cycle of recycled construction materials.

1.3 Study aim and objectives

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 sociolabeling, 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 hot spots in social sustainability aspects associated with recycled materials, which is very useful for strategic design for waste recycling, especially for the improvements of social sustainability performance of recycled materials.

2 Research design

This study is mainly consisted of two stages: model development and case study. In the first stage, a S-LCA model, SSG model, is developed for quantitative evaluation of recycled materials, following the four-phase structure of S-LCA. The first phase is goal and scope definition of the relevant stakeholder categories and subcategories and the selection of indicators. The second phase is inventory analysis that mainly focuses on data collection. Social life cycle impact assessment and comparative sustainability interpretation are the third and fourth phases, respectively. The overall research design of this study is shown in Fig. 1, which is developed based on the established guidelines for S-LCA (UNEP/SETAC 2009, 2011, 2013) and LCA for ISO standards (ISO 2006a, b). The detailed procedures for identifying stakeholder categories and impact subcategories, selecting indicators, collecting data, and benchmarking the indicator values are provided in Section 3.

The second stage of the study is to conduct a S-LCA case study of recycled construction materials in Hong Kong. The performance of recycled construction materials is compared with the conventional natural materials. This comparative case study has been conducted by using real data from the respective manufacturers (details will be provided in Section 4).

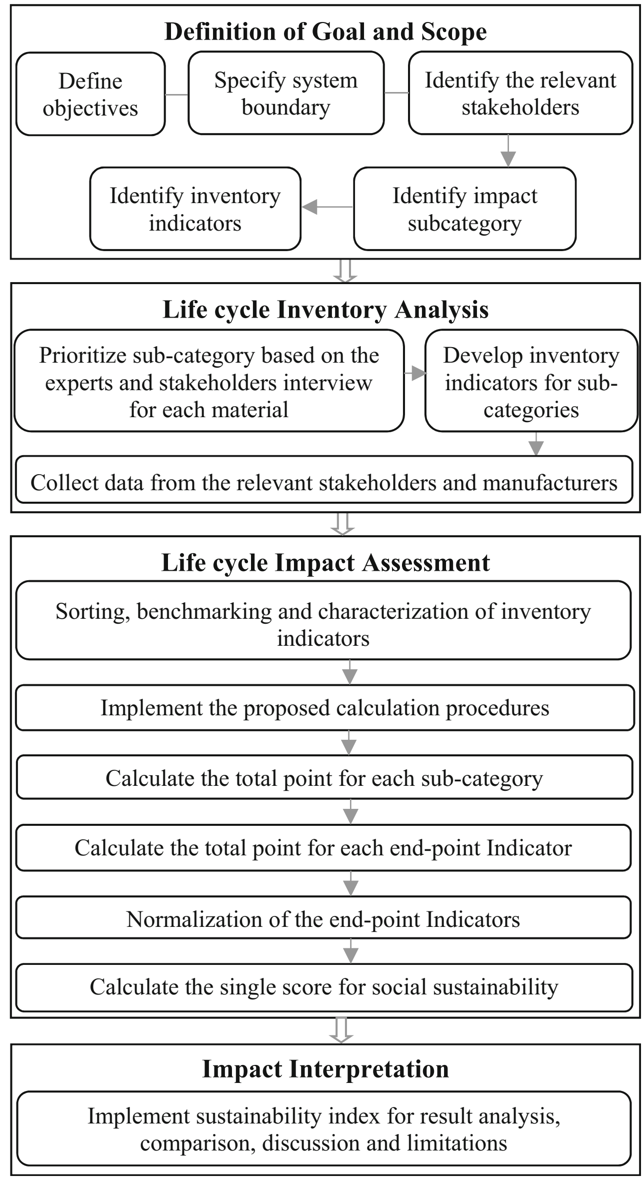


Fig. 1 Schematic illustration of the proposed S-LCA design

3 Development of the SSG model

The SSG model was proposed based on the UNEP/SETAC guidelines published in 2009 (UNEP/SETAC 2009) and the methodological sheets published in 2013 (UNEP/SETAC 2013), 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-step research approach was used in this study; the first step is a qualitative research based on the expert interviews to identify, select, and prioritize the relevant stakeholder categories and impact subcategories, and the second step is an operational research based on a case-specific survey to collect the required data. The choice of stakeholder

Table 2 List of stakeholder 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)
Producer	ISO (2010), GRI (2013), this study
Relevant stakeholders (socioenvironmental performance)	Henke and Theuvsen (2014), De Luca et al. (2015), this study

categories is based on the recommendations of various standards and literatures (Table 2). 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; GRI 2013).
(ii) Stakeholder categories and impact subcategories 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 indicators (compiled from UNEP/SETAC methodological sheets and GRI guidelines) and variables toward 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.
(vi) Simple calculation and grading systems for result interpretations.

3.1 Goal and scope definition

The goal and scope definition phase defines the overall objectives, system boundaries, 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 that can be used to assess and compare the social sustainability of construction materials. Although selection of construction materials is the primary application of the SSG model, the proposed methodology can be potentially applied for comparative assessment of other products.

System boundary specifies the criteria of including unit processes as part of product system (ISO 2006a). In environmental LCA, the product system embraces the processes in different life cycle stages within the system boundary and defines the inputs and outputs of energy and materials for each unit process. In a S-LCA study, the product system should include those processes that are directly related to the manufacturing activities, as well as the social impacts derived from the use phase (Hosseinijou et al. 2014). While system boundary determines the scope of a S-LCA study, the level of details may vary across different studies. Accordingly, the selection of system boundary should be object-oriented. Therefore, the product system of a S-LCA study should include the relevant social components, i.e., the stakeholders who are involved in or affected by the manufacturing, transporting, using, and disposing stages of a product, and these stakeholders normally refer to the manufacturers, employees, workers, suppliers, distributors, the local community, recyclers, waste managers, etc. In order to encompass the relevant stakeholders of construction materials, this study covers the "cradle-to-grave" life cycle stages (Fig. 2), including raw materials extraction, manufacturing process, transportation, usage and end-of-life treatments (disposal or recycling), and their associated stakeholders, such as producers, suppliers, recyclers, managers, planners, the local community, etc.

In S-LCA, many of the data used are qualitative and semi-quantitative. But the qualitative data is quite hard to be expressed by functional unit (FU) (Benoit et al. 2010; Benoit-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 environmental 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, since the scoring system is very important for capturing both the quantifiable and unquantifiable data (Hosseinijou et al. 2014). The adequacy of a S-LCA methodology heavily depends on how the unquantifiable data are coped with. Hence, the scoring system developed in the SSG model will be used to translate all inventory data (both additive and descriptive) to impacts in a

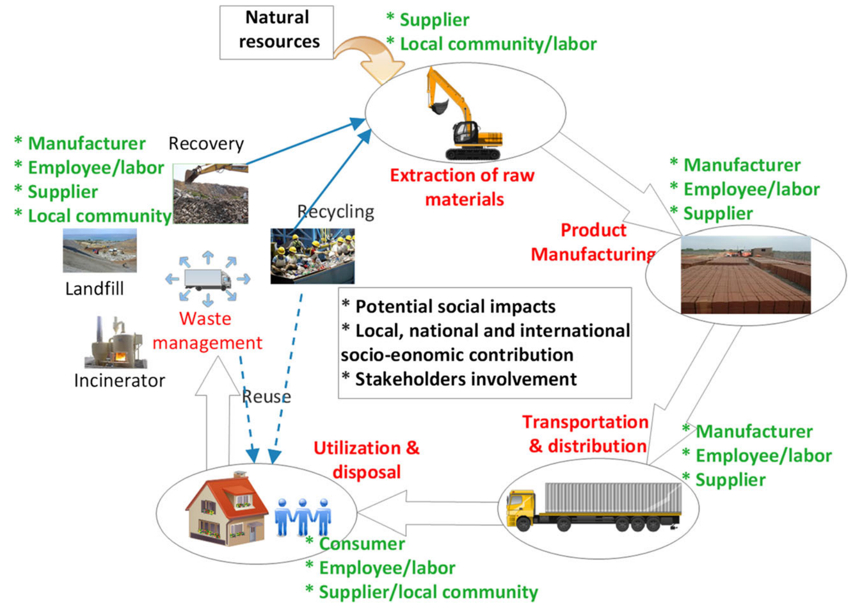


Fig. 2 The system boundary for the SSG model

comprehensive way. In addition, the benchmarking approach has been adopted for all data to capture the real impacts before applying in the scoring system (Section 3.3.1). Finally, three equations have been proposed for aggregation of the impacts (from indicators to subcategory level, then to endpoint category level, and finally to single score) (described in Section 3.3.2). Therefore, the SSG model will use an effective scoring approach to convert the social performance to social sustainability, given by a newly proposed sustainability index.

3.2 Life cycle inventory analysis

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 categories of a product life cycle depend on the product chain. In LCI phase, it is important to define and select the stakeholder categories, impact subcategories, 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 dimension, and it is still under debate on how sustainability performance can be measured for products (Finkbeiner et al. 2010; Benoit et al. 2010; Wu et al. 2014; 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 1 and 2). This study follows the four stakeholder categories proposed by UNEP/SETAC (2009), namely workers/employees, the general public (local community), government and society, and traders of the materials. A producer is responsible for significant social-economic impacts of construction materials and, therefore, is included as a separate stakeholder category according to the guidelines provided by GRI and ISO social responsibility (GRI 2013; ISO 2010). Moreover, an additional category, i.e., socioenvironmental performance of the material/product, is also included to consider other relevant stakeholders, such as recyclers. Several S-LCA studies also emphasized the importance of including the environmental impacts of a product in social analysis (Hosseinijou et al. 2014; Henke and Theuvsen 2014; De Luca et al. 2015). Although environmental aspects are mainly included in the environmental LCA, in the S-LCA of recycled construction materials, the environmental aspects cannot be neglected, as recycling systems also carry a significant social impact which should be included in a sustainability assessment. For example, several green building rating systems (e.g., BEAM Plus, LEED, BREAM, etc.) reward credits to the assessed buildings using recycled materials, with sound waste management and appropriate emission reduction (Wu et al. 2016). As the SSG model is constructed for assessing the social sustainability for recycled materials, assessing the socioenvironmental performance of the concerned materials is particular important. Therefore, socioenvironmental performance has been included as a separate category in the model.

Linking subcategories to an endpoint category is a challenge in S-LCA. To address this issue, Blom and Solmar (2009) proposed to use a separate impact indicator to represent each subcategory, whereas another method of linking subcategories to most of the impact categories was adopted by Franze and Ciroth (2011). In the SSG model, the possible subcategories were selected according to the guidelines of UNEP/SETAC (2009, 2013), GRI (2013), and BECL (2013) and further screened based on the objective of the study, target materials, and expert's suggestions. Subsequently, 30 relevant subcategories were selected for constructing the SSG model. Some of the impact subcategories were excluded from the model. For example, the subcategory "consumer privacy" under the stakeholder category of "producer of the material" was excluded, as this is not relevant to construction materials recycling in Hong Kong. It should also be noted that some subcategories, such as "child labor" and "equal opportunity/discrimination," have already been included as indicators of the subcategory "fair salary and employee characteristics," while "secure living conditions" has been included as an indicator in the subcategory of "safe and healthy living conditions" of the SSG model (see the Electronic Supplementary Material, S1). In addition, the SSG model can be used in other geographical regions, given further modification of the subcategories based on specific case study design. After identification of the subcategories for each stakeholder category, inventory indicators were defined and selected based on the guidelines provided by UNEP/SETAC (2013), GRI (2013), BECL (2013), ISO (2010), and other studies. Finally, the subcategories and inventory indicators were revised and then verified by the experts in the relevant fields.

The structure of the proposed SSG model is shown in Fig. 3. The model consists of 6 stakeholder categories, 30 impact subcategories, 6 endpoint categories, and a sustainability index (also called single score).

A mid-point category shows the impact from the cause-effect chain (e.g., real phenomena), while an endpoint category may facilitate more structured and informed weighting, particularly across subcategories. In addition, the endpoint level is more understandable and easily comparable as the complexity of a wide range of mid-point categories is reduced (Dong and Ng 2014). In the SSG model, the results can be presented in both ways (e.g., mid-point and endpoint categories). The results of the mid-point and the endpoint categories for the case study are described in Sections 4.2 and 4.3.

3.2.2 Descriptions of associated categories and subcategories

The first stakeholder category is the producer of the concerned materials which includes five impact subcategories 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 impact subcategories 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), accessibility of resources, health and safety of the living environment, and attitude toward the concerned materials/products.

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

The fifth category is the traders of the materials/products, which is associated with the social consequences (e.g., fair competition, supplier relationships, intellectual property right, etc.) and corporate social responsibility of the traders/suppliers (shown in Fig. 3).

The sixth category is the socioenvironmental performance (associated with relevant stakeholders) shown in Fig. 3, which includes five different subcategories related to the environmental management systems for producing the concern materials. Several subcategories 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.

3.2.3 Hot spot identification

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

In S-LCA, prioritization was recommended by several studies (e.g., Benoît-Norris et al. 2012; Garrido et al. 2016; Zanchi et al. 2016). However, till now, only few studies (e.g. Hosseinijou et al. 2014) have used prioritization on the subcategories level. In this study, the SSG model uses the prioritization approach to identify the most significant subcategories. The indicators for each subcategory have been developed and then verified by the experts. The weighting factor for hot spot identification is shown in Table 3, which is developed based on the scale of importance (or relevance), e.g., very important (or highly relevant) to not important (or irrelevant) with the scale of 1.00 to 0.00 to the subcategories. Scaling of

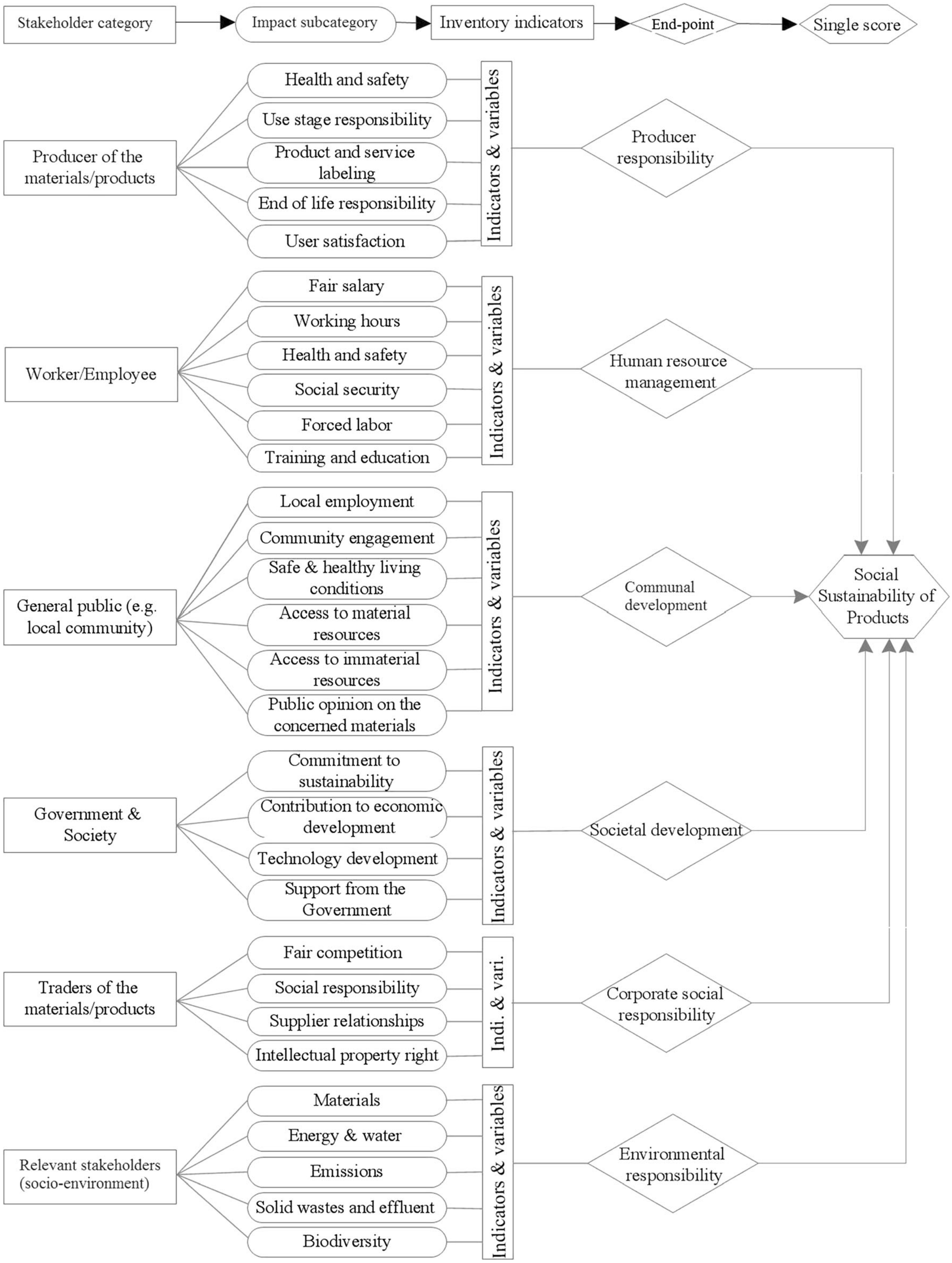


Fig. 3 The structure of the proposed SSG model

subcategories can be performed based on the proposed five scales in order to identify the appropriate subcategories with their magnitudes associated with the studied materials/products. After that, the hot spot can be identified from the predefined subcategories through the experts' interviews.

3.2.4 Data collection

For S-LCA, site-specific first-hand data is more desirable than national level data or database (e.g., social hotspot database). This is because the national level data may be too broad and

Table 3 Prioritizing scale for subcategory (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

hardly applicable to a specific product. In addition, the limitations for using social database have been identified by Hosseinijou et al. (2014). Therefore, it is preferable to use site-specific data in the SSG model, though the data collection is rather complex and time-consuming.

Unlike environmental LCA, 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 mainly interviews with the human resource department of the concerned companies, employees/workers, industry engineers, relevant researchers, community members, suppliers, and consumers/users of the materials. Moreover, national and international data provided by several organizations are also needed for referencing or benchmarking the indicators. The data collection procedure for the proposed SSG model is given in Fig. 4. It is important to mention that combinations of case-specific data based on expert interviews are necessary to the model implementation.

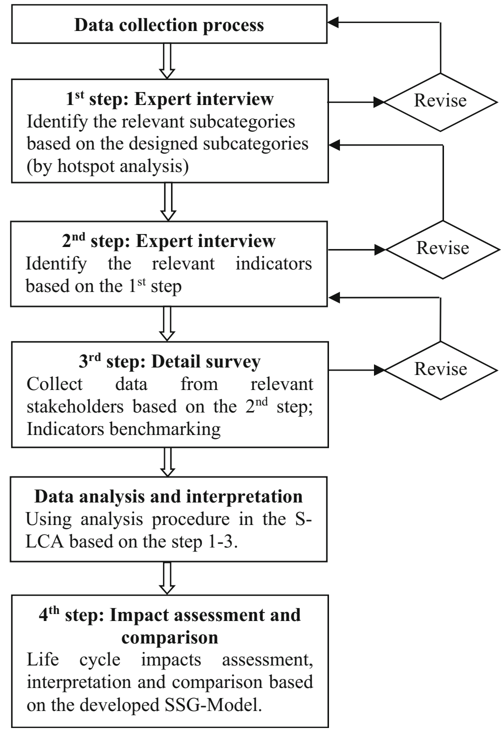


Fig. 4 Data collection procedure for the proposed SSG-model

3.3 Life cycle impact assessment (LCIA)

3.3.1 Indicators benchmarking

After collecting the case-specific data, it is important to classify different 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. As a large number and a variety of data are needed in S-LCA study, some of those data cannot be benchmarked with national data. This is because the best practice or reference may not well set for those data nationally. To overcome this situation, internationally set thresholds, for instance, World Bank data, International Labour Organization standards, ISO 26000, etc., can be used as reference points (Ciroth and Franze 2011). After benchmarking all data, the corresponding score needs to be given. A Likert scaling approach is proposed for scoring indicators (shown in Table 4). It is noted that the possible score range is "0.00" to "1.00" 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, the 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 4.

Table 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

3.3.2 Impact calculation

All the indicators will have specific points based on benchmarking for each subcategory. 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 4, and an example is provided in the Electronic Supplementary Material, S2). The SSG model used endpoint indicators which can be helpful for identifying the impact pathway and also achieving the final goal of the study. It can be seen from Fig. 3 that the SSG model uses six endpoint 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 subcategories. 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 subcategory should be sufficiently large to achieve the objective of that subcategory. In this model, characterization is needed to define the indicator score based on the respondents' response and benchmarking. The normalized score of a subcategory can be calculated by using Eq. (1). The weighting factor (coefficient of indicator based on Table 3) will be determined based on the expert interviews for hot spot identification (based on the importance of each subcategory).

$$SS_a = \frac{\left[\sum_{n=i}^{I} I_i \times COI\right]}{I_n} \tag{1}$$

where,

SS_a = net score of subcategory "a" (score should be within 0.00 to 1.00).

I_i = indicators "i" (benchmarked score based on Table 4).

I_n = number of indicators of subcategory "a."

COI = coefficient of indicator "i" (i = 0.00 to 1.00 based on Table 3).

The normalized net score for each endpoint indicator can be calculated by using Eq. (2).

$$SE_a = \frac{\sum_{n=i}^{S_c} SS_a}{\sum_{n=i}^{S_c} COI} \tag{2}$$

where,

SE_a = net score of endpoint category "a" (score should be within 0.00 to 1.00).

S_c = subcategory.

SS_a = sum of the total score of all subcategories "a."

COI = sum of the total coefficient of endpoint indicator "a."

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

$$SSS = \frac{\sum_{n=i}^{S_E} SE_a}{\sum_{n=i}^{S_E} (I_a \times W_f)} \tag{3}$$

where,

SE_a = Sum of the total normalized score of all endpoint indicators (n = a, b, c, ….f).

I_a = endpoint indicators "a."

S_E = endpoint category.

W_f = weighting factor of endpoint indicator "a" (W_f is assumed to be 1 for all endpoint indicators).

The impact calculation hierarchy is shown in Fig. 5.

3.4 Impact interpretation

According to ISO 14040 (2006a), the results of 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 subcategory and endpoint scores by using Eqs. (1) and (2).

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

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 locally from the recycling of construction and demolition (C&D) waste and also from locally generated waste glass (postconsumer glass bottles) for lower grade concrete applications (e.g., paving blocks) (Hossain et al. 2016a, b). Recycled aggregates from C&D waste can also be used as engineering filling materials (Poon and Chan

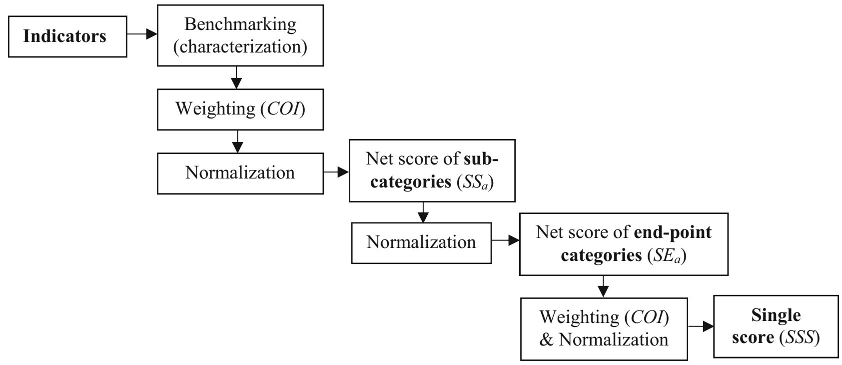


Fig. 5 Impact calculation hierarchy toward SSS

2006; Ebrahim and Behiry 2013). However, the recycling rates of using the recycled aggregates derived from the above waste materials are generally low (Hossain et al. 2016a).

This case study assessed the sustainability based on social performance using the SSG model of natural and recycled aggregates. It is believed that the study will help to improve the understanding of social sustainability performance of the construction industry and ultimately contribute to adoption of more sustainable construction materials. In addition, the developed SSG model can be applied as a complementary model to environmental LCA in the construction industry for promoting sustainable construction.

4.1 Inventory analysis

The necessary information for this case was collected from the respective manufacturers, suppliers, and associated stakeholders. As mentioned above, a twofold research approach is used in this study: (i) the qualitative research based on the expert interviews to prioritize the subcategories 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 Fig. 1, and the data collection procedure followed those in Fig. 4. The inventory analysis followed the SSG model described in Section 3.2. To implement the SSG model for construction materials, an expert and stakeholders survey was conducted to identify the "hot spot" by selecting subcategories based on the relevance and importance designed in Fig. 3. More than 100 stakeholders were invited to participate in this online survey through Google forms (see Electronic Supplementary Material, S4). Stakeholders were asked to identify and select the relevant subcategories based on the prioritization scale mentioned in Table 3. Diverse groups 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 with the response rate of about 38%. The background of the participants for the hot spot identification is given in Fig. 6.

In the third stage of data collection (Fig. 4), the case-specific core data are obtained. The inventory data for producing recycled aggregates (for both waste glass and C&D waste) were collected from the suppliers, managers, and workers (recycled material processing) 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 aggregate manufacturers is hidden due to the confidentiality concern.

4.2 Impact assessment

All the questionnaires for hot spot 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 subcategory where the highest value was 0.905 and the lowest value was 0.474. Based on the approach, the mid-point results were calculated and then ranked according to the average score of each subcategory (Table 6).

The results for prioritization of the subcategories are given in Fig. 7, where the hot spots are marked as dark color

Table 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/unsatisfied
0.00–0.20	E	Highly unsustainable	Strongly negative/highly unsatisfied

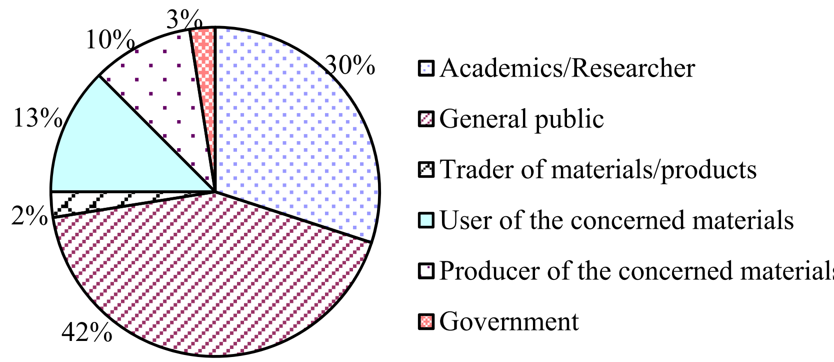


Fig. 6 Experts and stakeholders questionnaire survey for hot spot identification

implying that the subcategory is "very important." The survey results indicated that four subcategories were identified as the "very important" subcategories for the construction materials among the subcategories mentioned in the SSG model structure (Fig. 3). They 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 socioenvironmental performance. In addition, nine indicators were identified as the "important" subcategories, ten indicators were identified as neutrally important, five indicators were identified as "less important," and two were identified as "not important." The subcategories that were rated as not important were excluded in further analysis.

Detailed inventory data were collected from the respective stakeholders based on the data collection procedures given in Fig. 4. Some indicators were additive and can be quantified as per FU, but most of them were descriptive. Therefore, to reduce the complexity of quantification in S-LCA, the rating approach was applied (described in Section 3—SSG model development). In this case study, national level average data were used when the case-specific data were not available. The collected data were then screened, benchmarked, and analyzed for interpretation. After that, the data were fitted in the benchmarking work sheets to assess the relative magnitudes for each indicator using the predefined scale (Table 4). For this case study, a total of 109 indicators were used within the 28 impact subcategories under the six stakeholder categories (further details can be found in the Electronic Supplementary Material, S1). An Excel work sheet was developed by incorporating all the stakeholder categories, impact subcategories, and indicators. The calculation equations (described in Section 3.3.2) were integrated in the work sheet to calculate the impacts based on the SSG model. Finally, the score of each indicator after benchmarking was input into the work sheet. The snapshot of the calculation work sheet is given in Fig. 8. In the calculation work sheet, the score of each indicator is entered in the first column (named indicators' score), and the weighting factor is given in the next column. The weighted score for each indicator is found at the third column, and the normalized score for each subcategory is given in the fourth column. The normalized score for each endpoint category is provided in the last column. Finally, the SSS is obtained from the weighting of the normalized scores of all endpoint indicators (using Eq. (3)). In the case that the indicators were not provided by the respondents, the corresponding cells are left blank and not included in the calculation. For example, in Fig. 8, the producer of recycled aggregate did not receive any noticeable complain from the users related to its safety issues (Fig. 8). An example of indicator benchmarking and calculation is given in the Electronic Supplementary Material (S2 and S3).

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 subcategories in order to display how the products affect the different subcategories 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 (Figs. 9 and 10).

Using the developed calculation work sheets (Fig. 8), the weighted score of all indicators and the normalized score of all subcategories and endpoint categories were calculated. The normalized scores of the subcategories for the natural and recycled aggregates are presented in Fig. 9. The normalized score of the subcategory "health and safety" for recycled aggregates from C&D waste under the stakeholder category of "producer 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

Table 6 Interval scaling approach for prioritizing subcategories

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

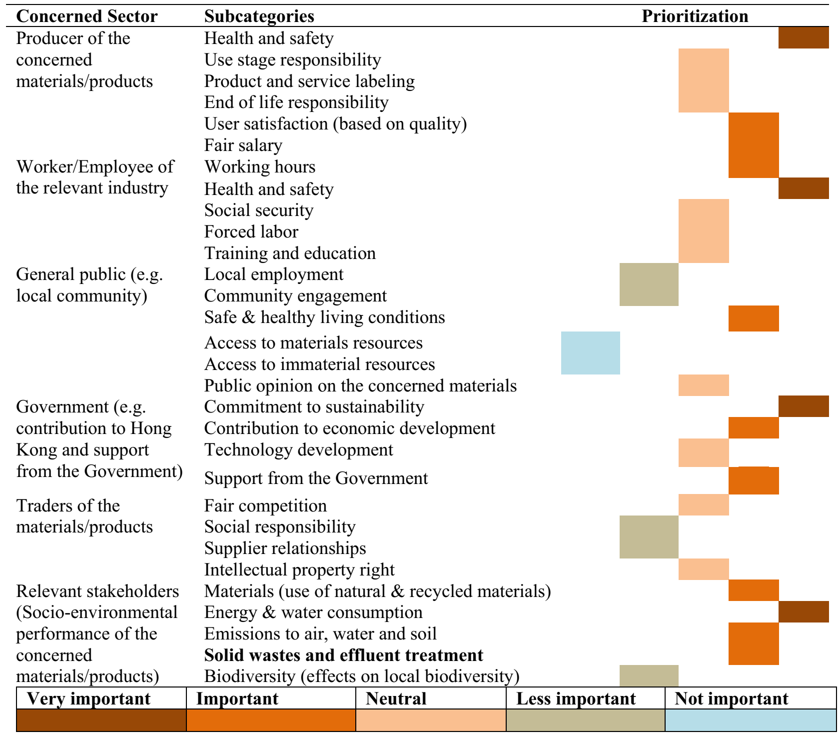
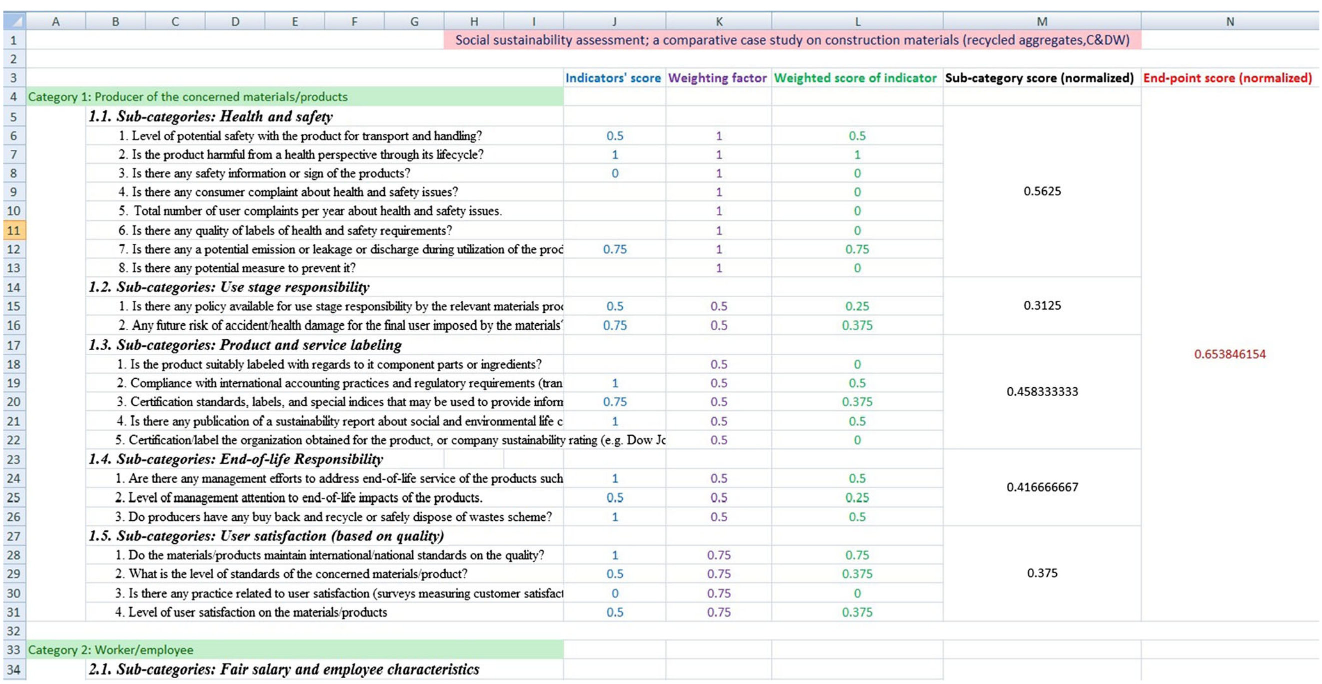


Fig. 7 Social hot spot identification of the concerned materials/products

impacts and safety issues during demolition, sorting, transport, and processing, as compared to other materials. 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 "socioenvironmental 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 reduce the associated environmental and social impacts due to landfill disposal. In contrast, natural aggregates are produced from virgin natural materials, leading to resource depletion and thus have negative social impacts. As a result, the score of natural aggregates is zero, indicating that the adoption of natural aggregates can cause negative social impacts.



	A–I	J	K	L	M	N
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 of the concerned materials/products					
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 inform	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***					

Fig. 8 Screenshot of the calculation work sheet

Fig. 9 Normalized score of subcategories for different aggregates

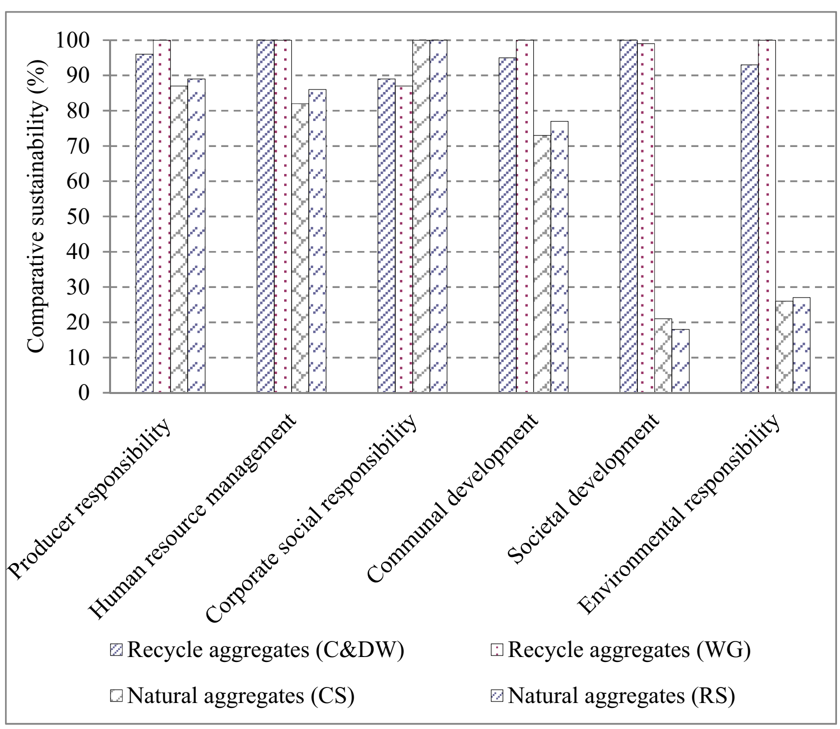
Category	Subcategories	Normalized score			
		CS	RS	C&DW	WG
Producer of the concerned materials/products	Health and safety	0.63	0.69	0.56	0.63
	Use stage responsibility	0.25	0.25	0.31	0.38
	Product and service labeling	0.33	0.33	0.46	0.46
	End of life responsibility	0.00	0.00	0.42	0.38
	User satisfaction (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
Relevant stakeholders (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]

4.3 Results interpretation

The normalized results of endpoint categories for the studied case are given in Fig. 10. It can be seen that natural aggregates have about 11–13% lower social sustainability score than recycled aggregates in Hong Kong at the endpoint category of producer responsibility. This is because the recycled aggregates have relatively higher score for some of the subcategories (e.g., product and service labeling, use stage, and end-of-life responsibility) than that of the natural aggregates. Recycled aggregates have higher end-of-life responsibilities, as they are entirely produced from waste materials. However, natural aggregates have higher score for health and safety issue and user satisfaction (based on the quality of the materials). Similar results were also found for the endpoint category of human resource management. This is because the score for most of the subcategories (e.g., fair salary, working hour, health and safety workplace for labor, social security, and

Fig. 10 Comparative endpoint sustainability of different aggregates



training) is relatively higher for recycled aggregates than the natural one. However, slightly higher score was observed for natural aggregates in the subcategory of force labor than the recycled one. The results are also consistent with previous studies in terms of the employment of construction labor in Hong Kong according to Dong and Ng (2015).

In addition, about 11–13% higher score was observed for the endpoint category of corporate social responsibility for natural aggregates. This is because the demands of aggregates are met by importing in Hong Kong, and there is a large social network involved. Therefore, a stronger business environment and supplier relationship is already in place for natural aggregates, as compared to the recycled one. At the endpoint category of community 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 processes involve the local community in the recycling activities and also promote healthy and safe living environment through transforming waste into a value-added resource for the local community. Recycled aggregate manufacturers collaborate with different governmental and nongovernmental organizations in the aspects of material recycling, public awareness promotion, and environmental protection activities.

In the category of societal development (e.g., contribution to Hong Kong), recycled aggregates attained higher social sustainability score than the natural aggregates. This is because firms may earn revenue through exporting the recycled products, and save money by avoiding importing materials, as well as the expenses associated with the disposal of waste materials to landfills. In addition, recycled aggregate manufacturers are contributing to the society and research studies to develop environmental technology. Unfortunately, support from the government to the manufacturers is not sufficient. Hence, the government should provide financial support, such as incentives and loans, as well as regulative support to develop specifications of recycled products, and other policies 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 have about 75% higher social sustainability in this category, as recycled aggregates reduces the need of landfill disposal and the associated environmental impacts. Figure 9 shows that recycled aggregates have higher scores for the subcategory of materials, mainly attributed to the adoption of waste materials. In addition, biodiversity also has a higher score, indicating that the effects of recycled aggregates on the local biodiversity are positive. However, there is no significant difference between the subcategories of energy and water consumption, 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.

The normalized SSS score obtained from the SSG model is given in Fig. 11. Based on the sustainability index provided in Table 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, and the general public. The corresponding scores for the natural aggregates are within the range of 0.41–0.60, indicating that the social performance of the products is moderately positive and the level of sustainability is *neutral* with grade *C*.

4.4 Sensitivity analysis for different weighting systems

As indicated above, equal weighting was considered for endpoint categories in this case study. In order to understand the influence by using different weighting factors, alternative weighting factors were tested to evaluate the sensitivity of the results. For the six endpoint categories, six alternative weighting scenarios were assessed (shown in the Electronic Supplementary Material, S5: Table 2). These weighting scenarios were selected to emphasize one endpoint category, which was given by a weighting factor 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 endpoint categories can affect the results. The sensitivity analysis results of changing the weighting factors are given in the Electronic Supplementary Material (S5: Table 3).

The sensitivity results showed that SSS of natural aggregates is significantly affected by varying the weighting factors of the endpoint categories, which is about 9–27% depending on the weighting scenarios 1–6, compared to the base scenario. On the contrary, less variation is found for recycled aggregates (about 0–10% compared to the base scenario). In addition, the change of SSS is about ±15–18% for recycled aggregates compared to the natural aggregates when all the

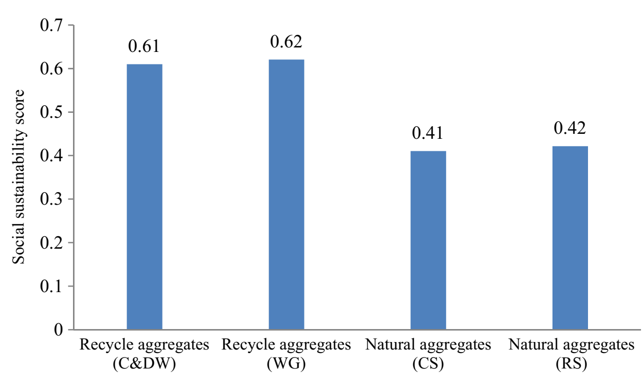


Fig. 11 Social sustainability of different aggregates

scenarios are considered. According to the sensitivity analysis, it is found that with smaller changes in the weighting factors, the change of SSS will not be significant, and hence, the equal weighting of the endpoint categories (e.g., base scenario in this case study) is an appropriate method and the results are reliable. In addition, no consensus has been achieved on different weighting systems in S-LCA study. Several studies have also supported that the endpoint 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 the endpoint categories would be helpful to improve the accuracy of the results.

5 Conclusions

Social sustainability assessment by S-LCA is still being developed due to the complex nature of social impacts, and many challenges exist, including quantification of the social impacts and establishment of new social stakeholder category/subcategories. To overcome the difficulties in S-LCA, case studies are needed. In this study, a S-LCA model is developed and a case study of recycled construction materials in Hong Kong is performed. The following conclusions can be drawn:

(i) A comprehensive SSG model for social sustainability assessment is developed for recycled materials with improvement in quantification and integration of socioenvironmental impacts to address the challenges in S-LCA.
(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 the social performance of other materials and products, in particular to assess the social sustainability and conduct comparative studies.
(iv) The case study reports that four subcategories, i.e., 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 subcategories for aggregates.
(v) According to the developed SSG model, the use of recycled aggregates in Hong Kong attains better performance in terms of social sustainability (31–34%) than natural aggregates.

As one of the first attempts of social sustainability assessment of recycled materials, the developed SSG model provides a comprehensive framework that can be used by the construction industry to understand the social performance through a life cycle perspective. Further study is still needed for sensitivity analyses, in order to unveil the interlinked social indicators and explore the social consequences in the complex social network. In addition, the integration of the S-LCA method in the conventional life cycle assessment software as well as in LCA methods will also be a topic for future research.

Acknowledgements The authors would like to thank all the stakeholders who participated in this research project and also to The Hong Kong Polytechnic University (Project of Strategic Importance) for funding support.

References

Arcese G, Lucchetti MC, Merli R (2013) Social life cycle assessment as a management tool: methodology for application in tourism. Sustainability 5:3275–3287
BECL (2013) Moving the construction sector towards sustainable development: industry engagement in developing corporate sustainability initiatives for SMEs in construction sector in Hong Kong. Business Environment Council Limited (BECL), Hong Kong
Benoit C, Norris GA, Valdivia S, Ciroth A, Moberg A, Bos U, Prakash S, Ugaya C, Beck T (2010) The guidelines for social life cycle assessment of products: just in time! Int J Life Cycle Assess 15:156–163
Benoît-Norris C, Aulisio D, Norris GA (2012) Identifying social impacts in product supply chains: overview and application of the social hotspot database. Sustainability 4:1946–1965
Benoit-Norris C, Vickery-Niederman G, Valdivia S, Franze J, Traverso M, Ciroth A, Mazijn B (2011) Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. Int J Life Cycle Assess 16(7):682–690
Blengini GA (2009) Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Build Environ 44(2:319–330
Blom M, Solmar C (2009) How to socially assess bio-fuels: a case study of the UNEP/SETAC Code of Practice for social-economical LCA. Master thesis, Division of Quality and Environmental Management. Lulea University of Technology, Stockholm
Bocoum I, Macombe C, Revéret JP (2015) Anticipating impacts on health based on changes in income inequality caused by life cycles. Int J Life Cycle Assess 20:405–417
Bozhilova-Kisheva K, Olsen SI (2011) Are recycled building materials more sustainable than the traditional ones? http://orbit.dtu.dk/fedora/objects/orbit:124158/datastreams/file_93065bf1-3a65-4b96-aea2-1e17c157f37b/content. Accessed 16 June 2017
Chhipi-Shrestha GK, Hewage K, Sadiq R (2015) Socializing sustainability: a critical review on current development status of social life cycle impact assessment method. Clean Techn Environ Policy 17:579–596
Ciroth A, Franze J (2011) LCA of an ecolabeled notebook. Consideration of social and environmental impacts along the entire life cycle. GreenDeltaTC GmbH, Berlin
Clift R (2014) Social life cycle assessment: what are we trying to do? In: Macombe C, Loeillet D (eds) Pre-proceedings of the 4th international seminar in social LCA. 19th–21st November. Montpellier, France, pp 11–16
De Luca AI, Iofrida N, Strano A, Falcone G, Gulisano G (2015) Social life cycle assessment and participatory approaches: a methodological proposal applied to citrus farming in southern Italy. Integr Environ Assess Manag 9999:1–14
Di Cesare S, Silveri F, Petti L (2014) The role of indicators in social life cycle assessment: results from a literature review http://bit.ly/1O9gf5F. Accessed 16 June 2017

Di Cesare S, Silveri F, Sala S, Petti L (2016) Positive impacts in social life cycle assessment: state of the art and the way forward. Int J Life Cycle Assess. doi:10.1007/s11367-016-1169-7

do Carmo BBT, Margni M, Baptiste P (2017a) Customized scoring and weighting approaches for quantifying and aggregating results in social life cycle impact assessment. Int J Life Cycle Assess. doi:10.1007/s11367-017-1280-4

do Carmo BBT, Margni M, Baptiste PE (2017b) Addressing uncertain scoring and weighting factors in social life cycle assessment. Int J Life Cycle Assess. doi:10.1007/s11367-017-1275-1

Dong YH, Ng ST (2014) Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong. Int J Life Cycle Assess 19:1409–1423

Dong YH, Ng ST (2015) A social life cycle assessment model for building construction in Hong Kong. Int J Life Cycle Assess 20:1166–1180

Dreyer LC, Hauschild MZ, Schierbeck J (2006) A framework for social life cycle impact assessment. Int J Life Cycle Assess 11(2):88–97

Ebrahim A, Behiry AE (2013) Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt. Ain Shams Eng J 4:661–673

Ekener-Petersen E, Moberg A (2013) Potential hotspots identified by social LCA—part 2: reflections on a study of a complex product. Int J Life Cycle Assess 18:144–154

Feschet P, Macombe C, Garrabe M, Loeillet D, Saez AR, Benhmad F (2013) Social impact assessment in LCA using the Preston pathway. The case of banana industry in Cameroon. Int J Life Cycle Assess 18:490–503

Finkbeiner M, Schau EM, Lehmann A, Traverso M (2010) Towards life cycle sustainability assessment. Sustainability 2(10):3309–3322

Foolmaun R, Ramjeeawon T (2013) Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. Int J Life Cycle Assess 18:155–171

Franze J, Ciroth A (2011) A comparison of cut roses from Ecuador and the Netherlands. Int J Life Cycle Assess 16(4):366–379

Garrido SR, Parent J, Beaulieu L, Reveret JP (2016) A literature review of type I SLCA—making the logic underlying methodological choices explicit. Int J Life Cycle Assess. doi:10.1007/s11367-016-1067-z

GRI (2013) Sustainability reporting guidelines (G4), Reporting principles and standards disclosures. Global Reporting Initiatives (GRI), The Netherlands

Grubert E (2016) Rigor in social life cycle assessment: improving the scientific grounding of SLCA. Int J Life Cycle Assess. doi:10.1007/s11367-016-1117-6

Haaster VB, Ciroth A, Fontes J, Wood R, Ramirez A (2017) Development of a methodological framework for social life-cycle assessment of novel technologies. Int J Life Cycle Assess 33(3):423–440

Hauschild MZ, Dreyer LC, Jørgensen A (2008) Assessing social impacts in a life cycle perspective—lessons learned. CIRP Ann Manuf Technol 57(1):21–24

Henke S, Theuvsen L (2014) Social life cycle assessment: socioeconomic evaluation of biogas plants and short rotation coppices. Proceedings in food system dynamics, Proceedings in System dynamics and innovation in food networks, Germany

Hossain MU, Poon CS, Lo IMC, Cheng JCP (2016a) Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach. Int J Life Cycle Assess 21:70–84

Hossain MU, Poon CS, Lo IMC, Cheng JCP (2016b) Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resour Conserv Recycl 109:67–77

Hosseinijou SA, Mansour S, Shirazi MA (2014) Social life cycle assessment for material selection: a case study of building materials. Int J Life Cycle Assess 19:620–645

Hunkeler D (2006) Societal LCA methodology and case study. Int J Life Cycle Assess 11(6):371–382

ISO (2006a) Environmental management—life cycle assessment—principles and framework (ISO14040). Geneva, Switzerland, ISO

ISO (2006b) Environmental management—life cycle assessment—requirements and guidelines (ISO14044). Geneva, Switzerland, ISO

ISO (2010) Guidance on social responsibility (ISO 26000). Geneva, Switzerland, ISO

Jørgensen A, Bocq AL, Nazarkina L, Hauschild M (2008) Methodologies for social life cycle assessment. Int J Life Cycle Assess 13(2):96–103

Jørgensen A, Lai LCH, Hauschild MZ (2010) Assessing the validity of impact pathways for child labour and well-being in social life cycle assessment. Int J Life Cycle Assess 15:5–16

Kloepffer W (2008) Life cycle sustainability assessment of products. Int J Life Cycle Assess 13(2):89–95

Kruse SA, Flysjo A, Kasperczyk N, Scholz AJ (2009) Socioeconomic indicators as a complement to life cycle assessment—an application to salmon production systems. Int J Life Cycle Assess 14:8–18

Labuschagne C, Brent AC (2006) Social indicators for sustainable project and technology life cycle management in the process industry. Int J Life Cycle Assess 11(1):3–15

Lehmann A, Zschieschang E, Traverso M, Finkbeiner M, Schebek L (2013) Social aspects for sustainability assessment of technologies—challenges for social life cycle assessment (SLCA). Int J Life Cycle Assess 18:1581–1592

Macombe C, Feschet P, Garrabe M, Loeillet D (2011) 2nd international seminar in social life cycle assessment—recent developments in assessing the social impacts of product life cycles. Int J Life Cycle Assess 16:940–943

Macombe C, Leskinen P, Feschet P, Antikainen R (2013) Social life cycle assessment of biodiesel production at three levels: a literature review and development needs. J Clean Prod 52:205–216

Manik Y, Leahy J, Halog A (2013) Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia. Int J Life Cycle Assess 18:1386–1392

Martínez-Blanco J, Lehmann A, Muñoz P, Antón A, Traverso M, Rieradevall J, Finkbeiner M (2014) Application challenges for the social LCA of fertilizers within life cycle sustainability assessment. J Clean Prod 69:34–48

Nazarkina L., Le Bocq A (2006) Social aspect of sustainability assessment: Feasibility of social life cycle assessment (S-LCA). Other. EDF, Moret-sur-Loing, France

Petersen EE (2013) Tracking down social impacts of products with social life cycle assessment. PhD thesis, KTH Royal Institute of Technology, Sweden

Petti L, Serreli M, Di Cesare S (2016) Systematic literature review in social life cycle assessment. Int J Life Cycle Assess. doi:10.1007/s11367-016-1135-4

Petti L, Ugaya CML, Di Cesare S (2014) Systematic review of social-life cycle assessment (S-LCA) case studies impact assessment method. In: Macombe C, Loeillet D (eds) Pre-proceedings of the 4th international seminar in social LCA. FruiTrop Thema, pp 34–41

Poon CS, Chan D (2006) Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Constr Build Mater 20:578–585

Ramirez PKS, Petti L, Haberland NT, Ugaya CML (2014) Subcategory assessment method for social life cycle assessment. Part 1: methodological framework. Int J Life Cycle Assess 19:1515–1523

Reveret JP, Couture JM, Parent J (2015) Socioeconomic LCA of milk production in Canada. In: Muthu SS (ed) Social life cycle assessment—an insight. Springer, Singapore, pp 25–69

Siebert A, Bezama A, O'Keeffe S, Thran D (2016) Social life cycle assessment: in pursuit of a framework for assessing wood-based products from bioeconomy regions in Germany. Int J Life Cycle Assess. doi:10.1007/s11367-016-1066-0

Sousa-Zomer TT, Miguel PAC (2015) The main challenges for social life cycle assessment (SLCA) to support the social impacts analysis of product-service systems. Int J Life Cycle Assess. doi:10.1007/s11367-015-1010-8

Swarr TE, Hunkeler D, Kloepffer W, Pesonen HL, Ciroth A, Brent C, Pagan R (2011) Environmental life cycle costing: a code of practice. Int J Life Cycle Assess 16:389–391

Traverso M, Finkbeiner M, Jorgensen A, Schneider L (2013) Life cycle sustainability dashboard. J Industrial Ecol 16(5):680–689

UNEP/SETAC (2009) Guidelines for social life cycle assessment of products. UNEPSETAC Life-Cycle Initiative, Paris, France

UNEP/SETAC (2011) Towards a life cycle sustainability assessment: making informed choices on products. UNEP-SETAC Life-Cycle Initiative, Paris, France

UNEP/SETAC (2013) The methodological sheets for subcategories in social life cycle assessment (S-LCA). UNEP-SETAC Life-Cycle Initiative, Paris, France

Valdivia S, Ugaya CML, Hildenbrand J, Traverso M, Mazijn B, Sonnemann G (2013) A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+20. Int J Life Cycle Assess 18(9): 1673–1685

Vinyes E, Oliver-Sola J, Ugaya C, Rieradevall J, Gasol C (2013) Application of LCSA to used cooking oil waste management. Int J Life Cycle Assess 18:445–455

Wu R, Yang D, Chen J (2014) Social life cycle assessment revisited—review. Sustainability 6:4200–4226

Wu Z, Shen L, Yu ATW, Zhang X (2016) A comparative analysis of waste management requirements between five green building rating systems for new residential buildings. J Clean Prod 112: 895–902

Zanchi L, Delogu M, Zamagni A, Pierini M (2016) Analysis of the main elements affecting social LCA applications: challenges for the automotive sector. Int J Life Cycle Assess. doi:10.1007/s11367-016-1176-8