The Environmental Effects of Building Construction Assessed Using a Life Cycle Assessment Model.

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A B S T R A C T

Building construction uses a lot of resources and energy. In spite of this, little effort has been made to look at how the construction phase affects the environment. This is particularly pertinent to Hong Kong, where the need for new construction is always rising. In this study, the Environmental Model of Construction (EMoC), a life cycle assessment (LCA) model, is created to assist decision-makers in evaluating the environmental performance of building construction projects in Hong Kong from the beginning to the end of construction. At the midpoint and endpoint levels, the model offers thorough evaluations of 18 environmental effect categories. With the input of project-specific data, EMoC can provide the results of over 200 intricate procedures. In order to assess how well these projects function environmentally, a public rental housing (PRH) project is loaded into EMoC. The findings show that material is the main cause of the environmental effects of the upstream phases of building public housing. The project under consideration produces 637 kg of carbon dioxide equivalent of emissions per square metre of gross floor space. Sensitivity analysis shows that adopting a higher proportion of precast concrete components can dramatically reduce environmental pollution. During the design, procurement, and construction phases of a building project, the model should enable decision-makers in identifying practical alternatives to lessen its environmental impact.

1. Introduction

While economic progress might result in a rise in quality of life, environmental harm to our pristine world can have a negative impact on human health and ultimately stunt economic expansion. The energy crisis, ozone depletion, and global warming are a few notable environmental challenges. The World Commission on Environment and Development (also known as the Brundtland Commission) first proposed the term "sustainable development" to manage environmental pollution and maintain development, with the well-known definition being "the development that meets the need of the present without compromising the ability of future generations to meet their own needs" [1]. A significant part has been performed in reducing and preventing environmental pollution in certain effect categories like global warming and ozone depletion by environmental protection forums like the Kyoto Protocol, Montreal Protocol, Agenda 21, and others. As a result, regional and national environmental strategies are developed. For instance, China's 12th Five Year Plan seeks to reduce carbon intensity (carbon emission per GDP) by 40 to 45 percent between 2005 and 2020 [2].

Given that building uses a lot of resources and produces a lot of pollution, achieving the objective of sustainable development entails managing the environmental effects of these vast construction activities. According to a report, 40% of the raw materials used in construction and civil engineering projects are used to create buildings [4], which accounts for 60% of the total [3]. Approximately 1 tonne of concrete is produced annually per person [5, 6]. Cement is a carbon-intensive substance that is a necessary component of concrete and accounts for around 5–7% of the world's anthropogenic carbon emissions [7]. In contrast to the steel and iron industry, which is accountable for 6.7% of global carbon emissions, construction utilises 16% of the annual total production of iron and steel [8]. Therefore, the business must estimate the environmental effects caused by the development of buildings. Currently, programmes for evaluating the environmental impact of buildings, such as Leadership in Energy and Environmental Design (LEED) [10]

Hong Kong, are widely applied and recognized as the assessment method to evaluate the environmental performance of buildings. These rating systems provide evaluation through a semi-quantitative scoring method, while the emitted substances cannot be systematically quantified. In addition, the assessment is focused on certain impact areas, e.g. indoor air quality, energy consumption, ozone depletion, water consumption, etc. Therefore, those impact categories which are beyond the evaluation scope are neglected, despite that emissions generated during construction may also be influential to those categories.

As an alternative to the building environmental assessment schemes, life cycle assessment (LCA) can quantitatively evaluate the environmental impacts of a product based on a large number of recognized impact categories. Because of its comprehensive coverage on environmental impacts and effectiveness of calculation, LCA has been intensively adopted as a decision support tool in both the business and political levels. Some studies applied LCA to estimate the environmental performance of construction materials [12,13], building operation [14], demolition methods [15], etc. In Hong Kong, an LCA model was established to assess the energy consumption of commercial buildings [16]. Moreover, an LCA study was conducted to evaluate the environmental impacts of construction materials used in public housing projects in Hong Kong [17]. Despite several studies [18e21] were focusing on the construction phase, none were specifically designed for Hong Kong. With limited storage space on site and in order to meet the continuous demand for housing facilities in Hong Kong, precast concrete is becoming increasingly popular, in particular in public housing estate construction. However, previous research studies have not paid enough attention to the adoption of precast concrete components in particular the processes within the precast yard where precast concrete products are manufactured. A holistic LCA model covering the processes of manufacturing and on-site installation of precast components is lacking.

To bridge the research gap and to help uncover the environmental impacts of construction projects, an LCA model known as the Environmental Model of Construction (EMoC) is developed to estimate the upstream life cycle stages of building construction up to the end of construction in a quantitative manner. Developed in Microsoft Excel, EMoC consists of a series of functional worksheets to facilitate environmental analyses on the construction activities according to a detailed breakdown of material, transportation, energy, waste treatment, etc. This enables, for instance, the adoption of precast and cast-in-situ concrete be analyzed in a transparent and structured basis. Besides, impact assessment is provided using both the midpoint and endpoint approaches so that the model results can be interpreted at different levels. This paper provides a step-by-step introduction of EMoC by exemplifying the model structure, assessment scope, collection of background data, calculation methods, as well as the model inputs and outputs. Finally, a case study of a public housing project in Hong Kong is presented to test the model performance.

2. Model development

Model scope

EMoC[1] is designed to provide assessment for high-rise concrete framed buildings, in particular for those residential buildings adopting precast concrete elements. The model can be applied in Hong Kong, and potentially be used in mainland China as well as other regions with further development needed. EMoC covers the ‘cradle-to-end of construction’ activities, which include the processes on or before the construction process, i.e. from raw material extraction, through material manufacturing, trans- portation, to the on-site construction (Fig. 1). Moreover, waste treatment of construction materials is also involved in the scope ofthe model.

Four types of resources are considered in EMoC, i.e. energy, material, equipment and labor. In terms of energy, the model analyzes three energy resources *viz*. electricity, diesel and gasoline. The production and usage of energy resources are embraced in the model while the transportation and combustion of fuels are also evaluated.

Construction materials refer to both the permanent and temporary materials whereby the environmental pollutions generated from material manufacturing and transportation as well as the waste treatment of materials are estimated in EMoC. Besides, the delivery of equipment and the fuel consumed by equipment on-site along with the environmental impacts resulted from labor transportation are also scrutinized.

On-site construction activities are the primary focus of EMoC. The model is capable of calculating the environmental impacts of over 200 construction activities, in particular those related to the concrete work. The environmental impacts of precast and cast-in-situ concrete can be evaluated independently. Apart from concrete, the model can be used for evaluating other construction activities such as ground work and masonry.

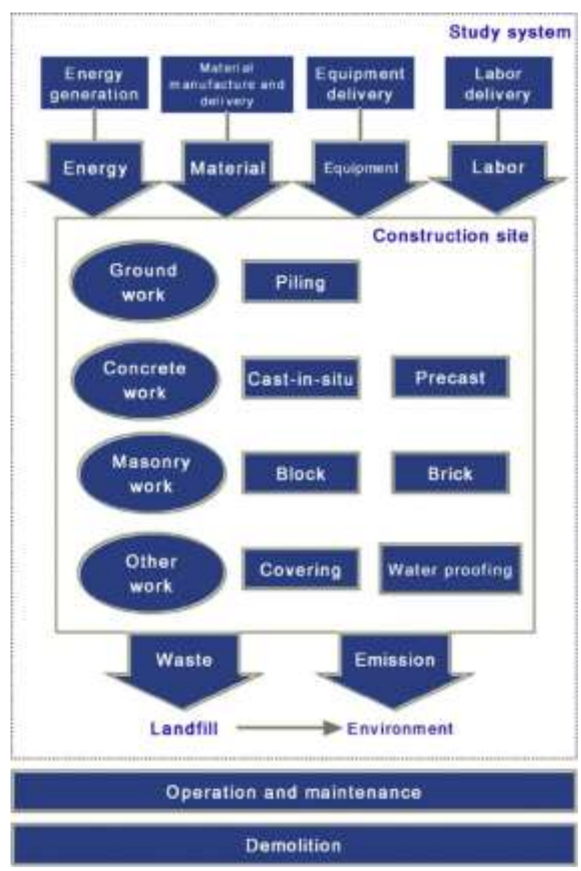


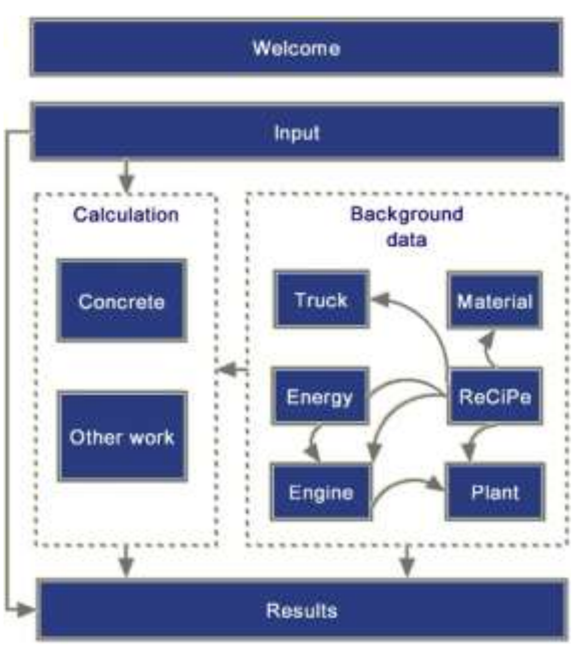
Fig. 1. Schematic illustration of the processes considered in EMoC.

Model design

EMoC is composed of 11 worksheets which fulfill various functions including data input, documentation of background data, calculation, and presentation of results (Fig. 2). The model allows users to enter the project-specific data into the 'Input' worksheet and obtain model outputs in the 'Results' worksheet. In Fig. 3, a screenshot of the 'Input' worksheet is provided, where users can enter the required information in the yellow (in web version) shaded cells. The 'Input' worksheet is composed of about a hundred parameters. The information collected is divided into eight sections and further details are provided in Table 1.

ReCiPe [22] is used as the life cycle impact assessment (LCIA) method in EMoC. LCIA is a critical phase in LCA to convert the life cycle inventory (LCI) into LCIA results. As required by ISO 14044 [23], an LCIA shall consist of characterization, normalization and weighting, in which characterization is a mandatory element while other two components are optional. In terms of characterization, two levels of characterization results are provided by ReCiPe, namely the midpoint and the endpoint outcomes. The endpoint LCIA is to estimate the damage to the areas of protection (AoPs) (i.e. human health, ecosystems, resource depletion), whereas the midpoint assessment intends to analyze the amount of emissions of various impact categories (i.e. climate change, ozone depletion, eutrophication, etc.). Since the midpoint and endpoint methods can generate different results, analysis using these two approaches is recommended [24]. To this regard, EMoC applies the midpoint and the endpoint approaches of ReCiPe. The midpoint and endpoint impact categories of ReCiPe are presented in Table 2. Normalization is a step to convert the characterization results to normalized values according to a reference system with certain temporal and spatial scope. Normalization results of different impact categories sharing the same unit are hence comparable. The normalization of ReCiPe is provided at two scales namely: Europe and globe. The global normalization scale is adopted in EMoC since this study focuses on constituencies outside Europe. Weighting is a procedure to modify the normalization results according to the importance of the impact categories. Weighting factors are assigned to the impact categories and the weighted results can be aggregated to compute a single score in order to represent the total environmental impact of a product. ReCiPe provides the characterization, normalization and weighting analyses under the endpoint approach, while its midpoint approach does not include any weighting.

Fig. 2. Model structure of EMoC.



The model evaluates dozens of construction materials that represent over 80% of environmental impacts caused by construction materials in a typical building. The inventory of precast concrete is obtained from the concrete industry in Hong Kong [25], while inventories of other construction materials are extracted from the LCI databases (e.g. Ecoinvent [26], US LCI [27]) in SimaPro 7.3.

Multiple waste treatment methods are provided in EMoC, including recycling, reuse, landfill and public fill. The transportation of waste materials to the treatment plants is also included in the estimation. It should be noted that EMoC is also capable of dealing with post-recycling (recycling after the construction project), whereas no project-specific information of pre-recycling (material with recycled content) is required in the 'Input' worksheet as the pre-recycling level of materials is assumed to be same as the inventory from the databases. For example, the pre-recycling level of primary aluminum in the Ecoinvent database is 32% and this percentage is used as the default in the model.

The electricity proportion in Hong Kong is obtained from the website of a local electricity plant. The electricity in Hong Kong is primarily generated by three fossil fuels, *viz*. gas (31%), coal (39%) and nuclear (29%) [28]. In addition to Hong Kong, the model documents the proportion of electricity mix in mainland China, facilitating analyses on construction projects in mainland China. The inventories of electricity generated by individual fuel are obtained from the Ecoinvent database.

In Hong Kong, the European Emission Standards are applied to regulate the environmental performance of trucks. Euro V came in force in December 2012 and all newly registered trucks should comply with the Euro V standards, while old trucks should be installed with dust reduction device as required by the Hong Kong Environmental Protection Department (HKEPD). Since the model is designed to be used in mainland China as well, where Euro III and Euro IV truck still exist, the model provides options of three emission levels for truck: i.e. Euro III, Euro IV and Euro V. Table 3 lists the truck models being considered in EMoC.

The model consists of two calculation worksheets, namely 'Concrete' and 'Other Work' worksheets, in which the background and input data are used to compute the environmental impacts. The 'Concrete' worksheet deals with the environmental impacts associated with concrete work, which includes the embodied emissions, transportation, use of equipment, waste treatment of material, etc. Ten concrete elements are analyzed *viz*. column, beam, façade, slab, staircase, partition wall, balcony, bathroom, refuse chute, and hanger wall. Concrete elements that are out of these ten types are calculated as other elements. Two construction methods relevant to concrete are studied, namely the cast-in-situ and precast concreting. The on-site activities of the cast-in-situ concrete involve complicated processes of delivery of raw materials, formwork, concrete placement, vibration, curing, etc. The use of precast concrete eliminates the process of formwork, concrete

Fig. 3. 'Input' worksheet of EMoC (only part of the worksheet is presented due to the length limit).

placement and curing, thereby only the embodied emissions and transportation of material are counted for precast concrete.

The 'Other Work' worksheet is designed to analyze those construction processes other than concrete work. This worksheet contains four sections, namely ground work, masonry work, surface work, and equipment. For ground work, the material consumed for piling and the soil to be removed as waste are considered. The section of masonry work deals with impacts associated with the manufacturing, delivery and waste treatment of brick and block. In the section of surface work, the manufacturing, delivery and waste treatment of finishing materials are analyzed. The last section in this worksheet is to cover the energy consumption of major equipment.

Table 1
Information collected in the Input worksheet.

Section	Information collected
User profile	Contact person, address telephone, date of data collection
General project information	Project name, location, gross floor area, number of units, construction time
Total resource consumption	Electricity, diesel, petrol, water, concrete, rebar
Concrete	Concrete type, wood formwork, steel formwork, precast concrete, cast-in-situ concrete, concrete elements, concrete waste, formwork waste
Transportation	One-way distance, truck mode, emission standard
Environmental protection	Level of dust control
Equipment	Excavator, forklift, hoist, mobile crane, tower crane, generator Operation hour, number of equipment
Other work	Ground work: concrete, rebar, soil waste Masonry work: brick, block Surface and external work: aluminum, cement, wood door, glass, mortar, plaster, PVC, tile, etc.

Table 2
The midpoint and the endpoint impact categories and the units of characterization models in ReCiPe [22].

Endpoint category	Unit	Midpoint category[a]	Abbr.	Unit
Human health	DALY	Climate change human health	CC(HH)	kg CO_2 e
		Ozone depletion	OD	kg CFC-11 e
		Human toxicity	HT	kg 1,4 e DB e
		Photochemical oxidant formation	POF	kg NMVOC e
		Particulate matter formation	PMF	kg PM10 e
		Ionizing radiation	IR	kg U235 e
Ecosystems	species$yr	Climate change ecosystems	CC(E)	kg CO_2 e
		Terrestrial acidification	TA	kg SO_2 e
		Freshwater eutrophication	FE	kg P e
		Terrestrial ecotoxicity	TET	kg 1,4 DB e
		Freshwater ecotoxicity	FET	kg 1,4 DB e
		Marine ecotoxicity	MET	kg 1,4 DB e
		Agricultural land occupation	ALO	m^2a

Table 3
Truck models in EMoC.

Class	Unit
Passenger car (Diesel)	persons km
Passenger car (Gasoline)	persons km
Lorry 3.5e7.5 t	t km
Lorry 7.5e16 t	t km
Lorry 16e32 t	t km
Lorry >32 t	t km
Truck mixer	t km

3. Case study

General description

The studied case is a public rental housing (PRH) project developed by the Hong Kong Housing Authority (HKHA) which can accommodate about 34,000 residents. There are altogether 13,300 flats, with 5100 flats and 8200 flats in Phase A and Phase B respectively. The construction of the project had started in 2009 and it was finished in 2013. A standard layout which is regarded as the New Harmony type (e.g. Ref. [29]) is applied in this project. The New Harmony PRH adopts precast elements for the construction of façade, slab, bathroom, staircase, refuse chute, etc. In the studied project, the proportion of precast concrete accounts for about 35% of the concrete volume.

Data collection and model input

The input data had been collected through a questionnaire survey addressed to the project manager, which was followed by several rounds of telephone interviews to consolidate the data. The questionnaire is designed based on the 'Input' worksheet of EMoC. Supplementary documents are acquired so that further information regarding the construction method and on-site usage of equipment is solicited.

The primary resources as applied in the studied project are shown in Table 4. The concrete consumption is 0.48 m^3 per square meter of GFA, which is less than skyscrapers like the International Commercial Center in Hong Kong but more than the low-rise buildings [30]. In the studied project, the waste rebar is sold as recycled metal, while the wood formwork is disposed after the construction. Further data pertinent to the concrete elements and other relevant information are not shown because of the confidentiality agreement.

The truck transportation distance and the corresponding Emission Standard are given in Table 5. In Hong Kong, the ready mixed concrete batching plant and the construction site are normally relatively close. In contrast, precast concrete elements are primarily manufactured in mainland China resulting in a much farther transportation distance. On the other hand, formwork and rebar are provided by local supplier. The delivery of ready mixed concrete is modeled by considering the truck mixers while the transportation of other materials is by means of 16e32 ton trucks.

In this case study, the operation details of equipment were obtained. Yet, the transportation details of equipment were not available. Therefore, it is assumed that a one-way distance of 10 km is needed for the transportation of equipment and trucks of 16e32 ton were used.

The studied project applied various environmental protection actions, such as the automatic sprinkler system along the haul road, floor wetting, hard pavement, and other dust control measures. As a result, the dust control level can be regarded as 'Highly Controlled'.

Table 4
Resources in the PRH project.

Item	Amount
GFA	3.1E05 m^2
No. of units	8,200
Electricity	2.8E06 kWh
Diesel	9.3E05 L
Water	2.6E05 L
Rebar	3.3E04 t
Concrete	1.5E05 m^3
Precast: cast-in-situ	7:13
Cast in situ concrete waste percentage	0.5%
Rebar waste percentage	6%
Wood formwork	5.3E06 kg
Steel formwork	3.6E04 t

Model results

Table 6 gives the midpoint characterization results of each impact category. The results are converted according to the functional unit of square meter of GFA. The GHG emissions of the studied project is 637 kg CO_2e, which is larger than 560 kg CO_2e as identified in a previous study [31] as EMoC covers more construction processes and materials.

Contributions from processes to the representative impact categories are analyzed in Fig. 4. It is found that material is the most influential part to the environmental impacts caused by the upstream processes, while energy consumption, transportation and waste treatment only account for a small proportion of the environmental impacts. The environmental impacts of individual materials are further analyzed in the pie charts so that any hotspots of environmental impacts can be detected. Steel and rebar are the materials contributing most to climate change, human toxicity, particulate matter formation, and fossil depletion. In contrast, agricultural land occupation is mainly contributed from wood/timber (i.e. formwork).

The endpoint characterization results of the PRH project are presented in Table 7. The results are given in two levels, i.e.: damage categories and impact categories. It is found that the damage to human health is 0.0015 DALY, which is mostly attributed to climate change, particulate matter formation and human toxicity. Damage to ecosystems is estimated at 8.38E-06 species.yr, mainly attributed to climate change and agricultural land occupation. The cost due to resource depletion is 2,741 US dollars which is mostly due to fossil depletion.

The endpoint single score is 74.8 per square meter of GFA, which is attributed to the damage to human health (62%), resources (33%), and ecosystems (5%) (Fig. 5). In terms of the influence from individual impact categories, human health is mostly affected by climate change, human toxicity, and particulate matter formation. Climate change itself is responsible for 37% of the single score while particulate matter accounts for 19%.

Sensitivity analysis

Sensitivity analysis is a method to investigate the influence from certain variables to the final results by changing the value of those

Table 5Transportation distance and emission standard of truck for major materials.

Item	Distance (one way)	Emission standard
Ready mixed concrete	0.3 km	Euro IV
Precast concrete	135 km	Euro IV
Formwork	70 km	Euro IV
Rebar	40 km	Euro IV

Table 6
Midpoint characterization results.

Impact category	Unit	Per GFA (m^2)
Climate change	kg CO_2 e	637
Ozone depletion	kg CFC-11 e	4.2E-05
Human toxicity	kg 1,4-DB e	285
Photochemical oxidant formation	kg NMVOC e	2.3
Particulate matter formation	kg PM10 e	1.8
Ionizing radiation	kg U235 e	89
Terrestrial acidification	kg SO_2 e	2.1
Freshwater eutrophication	kg P e	0.3
Marine eutrophication	kg N e	0.1
Terrestrial ecotoxicity	kg 1,4-DB e	0.1
Freshwater ecotoxicity	kg 1,4-DB e	9.7
Marine ecotoxicity	kg 1,4-DB e	10.0
Agricultural land occupation	m^{2}a	273
Urban land occupation	m^{2}a	7.9
Natural land transformation	m^2	0.1
Water depletion	m^3	6.3
Metal depletion	kg Fe e	648
Fossil depletion	kg oil e	170

variables. In this section, four groups of scenarios are performed to test the influence from timber formwork, precast concrete, transportation of precast components, and biodiesel.

Timber formwork

Timber formwork is the most influential factor to land transformation. In general, timber formwork can only be reused a limited times, because the contact surface of used timber formwork could be damaged, leading to defect of the finished concrete surface. In the PRH project, timber formwork was reused only once or twice. To study the environment impact due to the reuse of on-site timber formwork, three scenarios were performed: i.e. not reused, reused once (original scenario), reused twice (Table 8).

Compared to the original scenario, reusing timber formwork one more time can lead to a 2.7% decrease of the total single impact score. On the other hand, if the timber formwork is not reused, the single score can increase by 5.5%.

The influence from the amount of timber to the category of agricultural land occupation is further examined. It is found that the amount of timber used can determine the performance of agricultural land occupation. Reusing timber formwork twice can

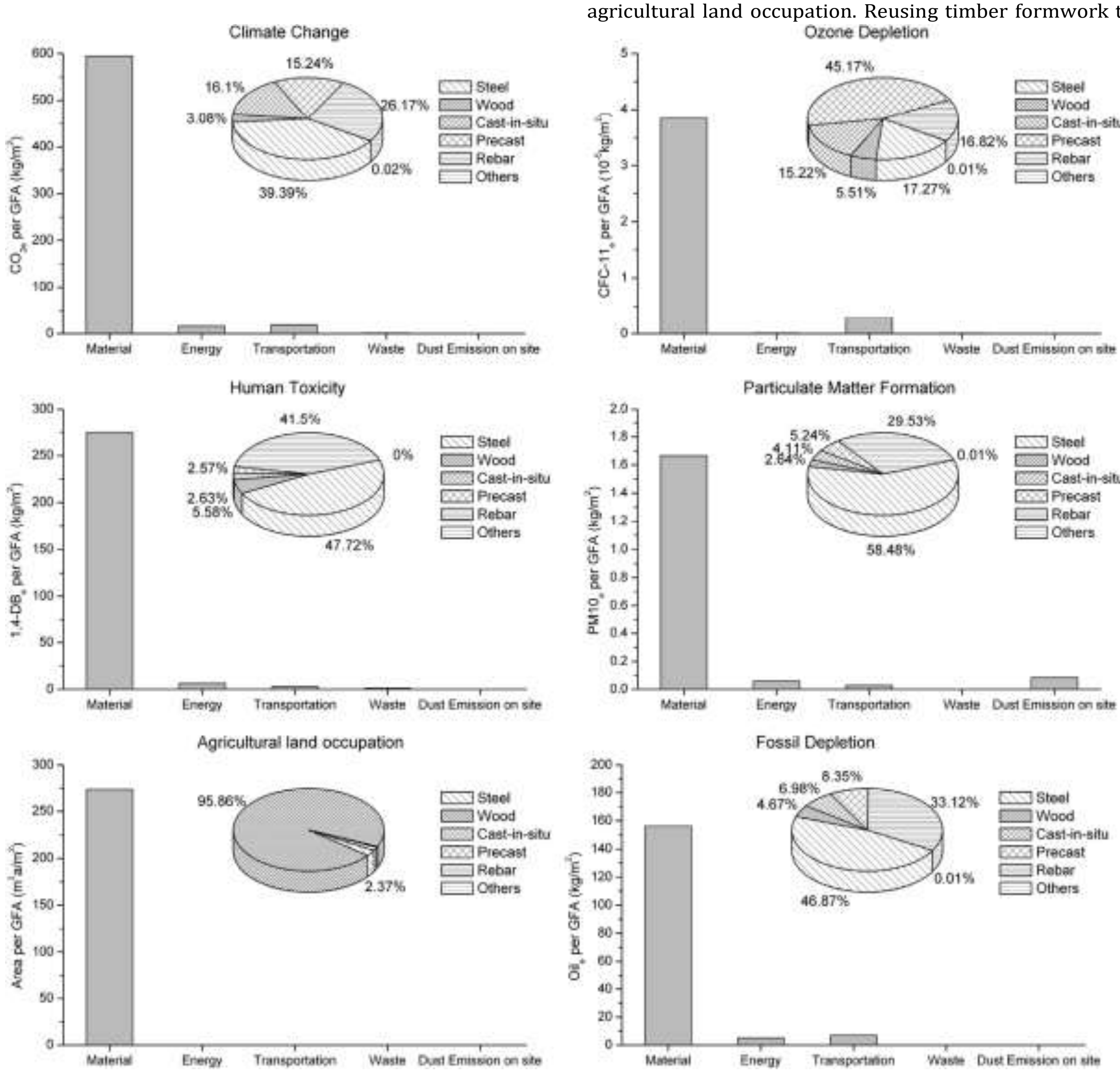


Fig. 4. Contribution analysis of the studied project in selected impact categories.

Table 7
Endpoint characterization results.

Damage category	Unit	Amount (per m^2 GFA)	Impact category	Amount (per m^2 GFA)
Human health	DALY	0.0015	Climate change human health	8.8E-04
			Ozone depletion	1.1E-07
			Human toxicity	2.0E-04
			Photochemical oxidant formation	8.7E-08
			Particulate matter formation	4.8E-04
			Ionizing radiation	1.4E-06
Ecosystems	species.yr	8.38E-06	Climate change Ecosystems	5.0E-06
			Terrestrial acidification	1.2E-08
			Freshwater eutrophication	1.2E-08
			Terrestrial ecotoxicity	1.5E-08
			Freshwater ecotoxicity	2.5E-09
			Marine ecotoxicity	8.0E-12
			Agricultural land occupation	3.1E-06
			Urban land occupation	1.5E-07
			Natural land transformation	1.5E-07
Resources	$	2,741	Metal depletion	46
			Fossil depletion	2695

reduce about 50% of the environmental impact on agricultural land occupation.

Precast and cast-in-situ

Precast concrete has been regarded as an environmental-friendly alternative to cast-in-situ concrete. To investigate the improvement of environmental performance due to the adoption of precast concrete, sensitivity analysis was carried out by changing the amount of precast concrete. In the original scenario, the proportion of precast concrete by volume is 35%. This value is altered to 0% and 10% (Table 9).

The results indicate that the adoption of precast concrete can significantly improve the environmental performance of the studied project. Should no precast concrete be used, the single score would be increased by 23.8%. If 10% of the total concrete volume is precast, the result is 16.6% larger than that of the original scenario. The observation points to a greater adoption of precast concrete in building construction.

Transportation of precast element

The precast concrete components in the studied project were manufactured in mainland China. The results of EMoC reveal that the transportation of precast elements from the precast yard to construction site is responsible for approximately 50% of the

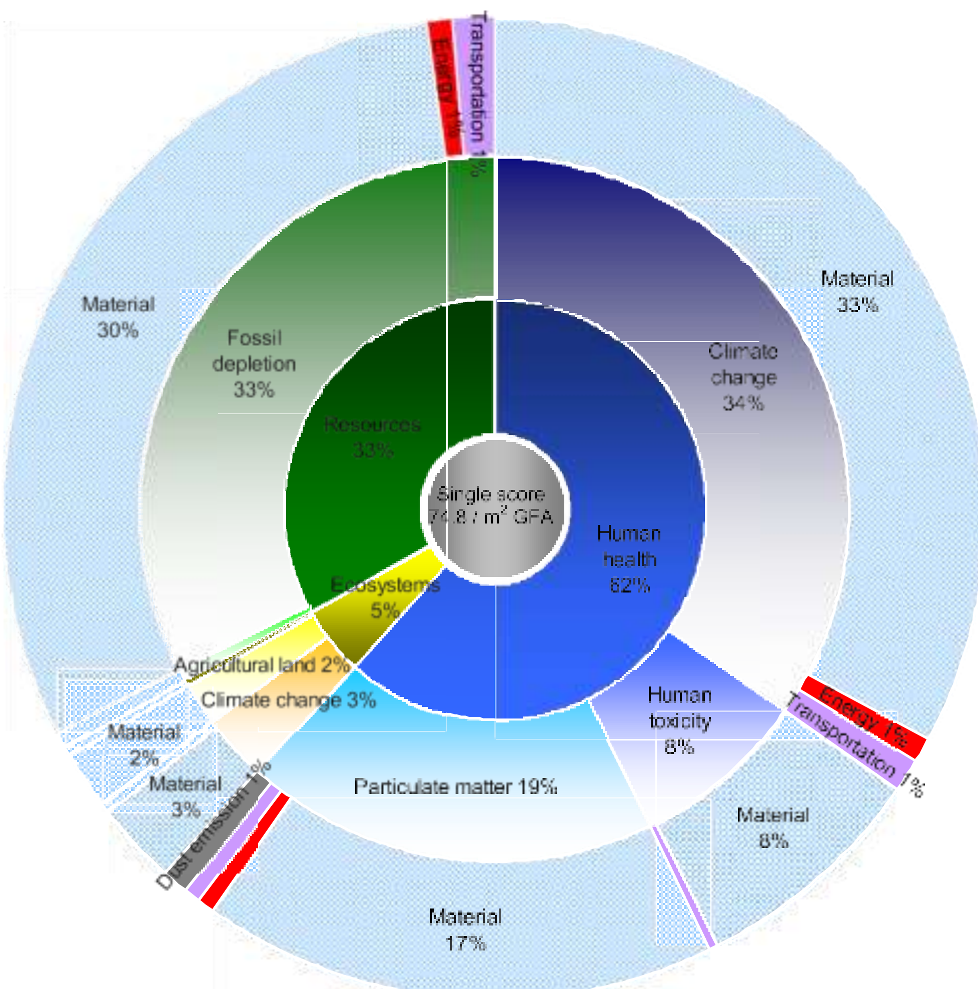


Fig. 5. Contributions from damage categories, impact categories and processes to single score. Endpoint results are used. The core circle is the total single score per m^2 GFA. The second ring is the contribution from three damage categories. The third ring is the contribution from 18 impact categories. The forth ring is the contribution from processes and phases of construction.

Table 8
Sensitivity analysis by changing the amount of wood.

Scenario	Wood (kg)	Single score m² per GFA	Change of single score %	Contribution of wood to single score%
Reused once	5.30E þ 06	74.9	N.A.	5.3%
Reused twice	2.70E þ 06	72.9	—2.7%	2.7%
Not reused	1.06E þ 07	79.0	5.5%	10.1%

Table 9
Sensitivity analysis by changing the amount of precast concrete.

Precast concrete (%)	Wood form amount (t)	Steel form amount (t)	Single score (per m² GFA)	Change of single score (%)
35%	5,360	36,040	74.9	N.A.
0%	8,247	55,446	92.7	23.8%
10%	7,422	49,901	87.4	16.6%

environmental influence of all transportation activities in the studied case. In the original scenario, the distance between the precast yard and construction site is 135 km. To examine the impact induced by the location of precast yard, two alternative scenarios were examined (Table 10).

It is found that the single score can be reduced by 1% if the precast yard is located 50 km from the construction site. In addition, the total environmental performance of transportation can be improved by about 30%. On the other hand, if the transportation distance is increased to 300 km, the single score will be 2% larger and the environmental impact due to transportation can be increased by over 50%. The sensitivity analysis of precast transportation indicates that the location of precast yard can significantly influence the environmental performance of the studied project.

Adoption of biodiesel

Biodiesel is an environmental-friendly alternative to petroleum diesel. When biodiesel is implemented, it should be blended with petroleum diesel in certain proportion by volume to prevent damaging the diesel engine. In general, there are three blend mixes: B5, B10 and B20. B5 refers to the diesel mix with 5% biodiesel and 95% petroleum diesel. In the original scenario, petroleum diesel is used for all the on-site construction equipment. To investigate the improvement of environmental performance due to the adoption of biodiesel, three alternative scenarios were scrutinized (Table 11).

The results demonstrate that the influence brought by different blend mixes of biodiesel in the studied project is insignificant. For example, if B20 is used in all the on-site equipment, only 0.24% of improvement in the impact score can be achieved and the changes are even more trivial for B5 and B10 biodiesel. The insignificant influence of biodiesel is primarily due to the small replacing proportion of biodiesel.

4. Discussion

EMoC is a LCA model developed to evaluate the environmental impacts of construction projects. The model can be applied in the early design stage for decision support as well as in the procurement and construction processes to provide information regarding the environmental performance of a building construction project. The model considers the upstream construction activities which encompass raw material extraction, manufacturing, transportation, and on-site construction. The usage and end-of-life demolition are, however, excluded. The omission of the downstream processes is due to the following considerations. Firstly, the duration of building construction is normally less than two years which makes the evaluation process more controllable and predictable. In contrast, the usage phase of a building can last for over 50 or even 100 years. The energy generation method and the using of the facility may change tremendously during such a long time horizon, which renders it difficult to use LCA modeling for the downstream processes. Another concern is that the downstream processes can be simulated using various energy modeling tools like Energy Plus, eQUEST, etc. Consequently, the downstream processes are not the focus of this research despite the inclusion of downstream processes may change the interpretation of the model results. Further research should be carried out to unveil the impacts brought by the downstream processes in future.

It should be noted that the model provides comprehensive analysis on 18 impact categories at both the midpoint and endpoint levels. Users can refer to the single endpoint score and/or results of individual impact categories. One can also focus on certain key aspects rather than all the 18 impact categories according to the specific needs of a construction project.

The case study of the PRH project helps to demonstrate how EMoC can be used to evaluate the environmental performance of a standard PRH project in Hong Kong and the results can be compared with comparable building projects or other studies. In the sensitivity analysis, different alternatives were examined to identify what possible improvements can be introduced to reduce the environmental impacts of this type of buildings. It is found that precast concrete can largely reduce the environmental pollution as compared to the cast-in-situ concrete due to the adoption of recyclable steel formwork in the precast yard rather than the reliance on temporary timberwork as in the case of the cast-in-situ concrete. Steel formwork can normally be reused for over 50 times before finally returned to the steel plant for recycling. On the contrary, timber formwork can only be reused once or twice and it has to be disposed o landfill as waste material.

Table 10
Sensitivity analysis by changing the transportation distance of precast concrete.

Transportation distance (one way)	Single score (per m² GFA)	Change of single score (%)	Contribution of transportation of precast elements %
135 km	74.9	N.A.	1.6%
50 km	74.2	—1.0%	0.6%
300 km	76.4	2.0%	3.5%

Table 11
Sensitivity analysis of biodiesel.

Blend mix	Biodiesel (%)	Single score (per m² GFA)	Change of single score (%)	Contribution of diesel (%)
B0	0%	74.91	N.A.	1.81%
B5	5%	74.87	0.06%	1.75%
B10	10%	74.82	0.12%	1.69%
B20	20%	74.73	0.24%	1.57%

5. Conclusions

building using a LCIA method. Through ReCiPe, a variety of impact categories can be analyzed to provide decision-makers with a set of comprehensive results on the environmental performance of the project. The model allows users to input project specific data and provides results for over 200 processes and items.

A case study of PRH has been conducted to test the model performance. It is found that in the upstream processes, material selection contributes most to the environmental impacts of a building project. The GHG emissions of the studied project account for 637 kg of CO_2e per m^2 of GFA. As for the energy consumption of the case project, it is 170 kg of oil equivalent per m^2 of GFA. The overall environmental performance of the studied case as represented by the single endpoint score is 74.8, with 62% being attributed to the damage of human health and 33% due to resource depletion. Sensitivity analysis reveals that the environmental impacts of the studied project can be reduced considerably by adopting a higher proportion of precast concrete components. However, the transportation of precast concrete elements is an important factor in order to achieve a better environmental performance. Since the use of timber formwork is harmful to the environment, it is suggested to replace it by alternative materials with higher recycled content.

The model results of the case study can be used to create a benchmark of environmental performance of residential buildings in future research, while the findings of the sensitivity analysis provide sensible suggestions on the selection of construction methods and formworking materials. Relevant stakeholders can consult for their building projects using the same approach to help determine the environmental performance and hence introduce appropriate measures to mitigate the environmental burden.

EMoC can be applied throughout different stages of project life cycle despite it is preferable to applying the model at the early design stage. The model can help improve our understanding on the environmental impacts caused by a building construction project. More importantly, developers or contractors can select an environmental-friendly alternative based on the results of EMoC. While the scope of EMoC is currently limited to the upstream stages, it can be expanded to encompass the downstream processes of operation, maintenance and demolition in future so that more accurate assessment on the environmental performance of a building project can be achieved.

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