LCIA OF IMPACTS ON HUMAN HEALTH AND ECOSYSTEMS

Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong

Ya Hong Dong · S. Thomas Ng

Abstract

Purpose Life cycle assessment (LCA) has been increasingly implemented in analyzing the environmental performance of buildings and construction projects. To assess the life cycle environmental performance, decision-makers may adopt the two life cycle impact assessment (LCIA) approaches, namely the midpoint and endpoint models. Any imprudent usage of the two approaches may affect the assessment results and thus lead to misleading findings. ReCiPe, a well-known work, includes a package of LCIA methods to provide assessments on both midpoint and endpoint levels. This study compares different potential LCIA results using the midpoint and endpoint approaches of ReCiPe based on the assessment of a commercial building in Hong Kong.
Methods This paper examines 23 materials accounting for over 99 % of the environmental impacts of all the materials consumed in commercial buildings in Hong Kong. The midpoint and endpoint results are compared at the normalization level. A commercial building in Hong Kong is further studied to provide insights as a real case study. The ranking of impact categories and the contributions from various construction materials are examined for the commercial building. Influence due to the weighting factors is discussed.
Results and discussion Normalization results of individual impact categories of the midpoint and endpoint approaches are consistent for the selected construction materials. The difference in the two approaches can be detected when several impact categories are considered. The ranking of materials is slightly different under the two approaches. The ranking of impact categories demonstrates completely different features.

In the case study of a commercial building in Hong Kong, the contributions from subprocesses are different at the midpoint and endpoint. The weighting factors can determine not only the contributions of the damage categories to the total environment, but also the value of a single score.
Conclusions In this research, the midpoint and endpoint approaches are compared using ReCiPe. Information is whittled down from the inventories to a single score. Midpoint results are comprehensive while endpoint results are concise. The endpoint approach which provides additional information of damage should be used as a supplementary to the midpoint model. When endpoint results are asked for, a LCIA method like ReCiPe that provides both the midpoint and endpoint analysis is recommended. This study can assist LCA designers to interpret the midpoint and endpoint results, in particular, for the assessment of commercial buildings in Hong Kong.

Keywords Building · Construction material · Environmental impact · LCA · LCIA

S. T. Ng (✉)
Department of Civil Engineering, The University of Hong Kong,
Pokfulam Road, Hong Kong, China
e-mail: tstng@hku.hk

1 Introduction

Life cycle assessment (LCA) is a promising method to account for the life cycle environmental performance of a product from raw material extraction, through manufacturing and transportation, to demolition and disposal. As required by ISO 14040, four phases are normally involved in a LCA study and they include: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation (ISO 2006b). The first phase is to define the study objectives, product system, target audience, functional unit, etc. In the life cycle inventory (LCI) phase, data are collected to provide the inventory results. In the third phase, life cycle impact assessment (LCIA), which is a complex process, converts

the LCI results into various category indicators. The LCI and LCIA results are then interpreted in the final phase in which sensitivity analysis or uncertainty analysis can be conducted.

When performing LCIA, assessors may adopt the midpoint and endpoint approaches. As defined in (ILCD 2011), the midpoint and endpoint approaches are characterization models which provide indicators at different levels. The endpoint approach evaluates the environmental impact at the areas of protection (AoP) level, such as human health, ecosystem, and resource. In contrast, the midpoint approach assesses the environmental impact at a level in cause-effect chain from the release of substance or consumption of resource to the endpoint level.

Using the midpoint LCIA methods, such as CML (Guinée 2001) and TRACI (EPA 2003), the environmental interventions are represented as a set of indicators including carbon dioxide (CO_2) for climate change, chlorofluorocarbon (CFC) for ozone depletion, nitrogen oxides (NO_x) for eutrophication, sulfur dioxide (SO_2) for acidification, etc. Since the midpoint approach concludes a set of indicators for dozens of impact categories, it is difficult to interpret the midpoint results (Yi et al. 2011). In contrast, the endpoint LCIA methods like Eco-indicator 99 (Goedkoop et al. 1999) convert indicators of the impact categories into three or four damage categories (i.e., AoP) only, i.e., human health, ecosystem, and resource, resulting in a relatively easier interpretation. The damage caused by environmental interventions is estimated in damage modeling through which damage factors are derived to facilitate the endpoint evaluation. Since LCA comprises LCI data over time and space, it is challenging to provide a characterization model at the endpoint level. The downside of the endpoint approach is that, due to the involvement of additional steps like the fate modeling and damage modeling, such a complex characterization model could introduce some uncertainties to the endpoint results (Finnveden et al. 2009). Bare et al. (2000) advocated that a consistent framework is inevitable to provide the LCIA results at both the midpoint and endpoint levels. Such a request led to the development of ReCiPe (Goedkoop et al. 2009; Heijungs et al. 2003). Although ReCiPe strives to provide the midpoint and endpoint assessments in a consistent way, the implementations of the two approaches may result in different interpretations.

While many literature reviews, statistical analyses, and case studies have been conducted to compare the existing LCIA methods (Notarnicola et al. 1998; Schulze et al. 2001; Pennington et al. 2004; Brent and Hietkamp 2003; Dreyer et al. 2003; Renou et al. 2008; Landis and Theis 2008; Amani and Schiefer 2011; Berger and Finkbeiner 2011; Pizzol et al. 2011; Cavalett et al. 2013; Monteiro and Freire 2012), there has been no consensus on when to use an endpoint-based method and how to help the end users interpret the endpoint results. In some LCA applications, such as Environmental Product Declaration (EPD)

(ISO 2010) and its superstructure Product Category Rules (PCR) (CEN 2012), a midpoint LCIA method of CML is selected. Others (EMSD 2006) may prefer an endpoint LCIA method like Eco-indicator 99.

Until now, very few studies have been conducted to compare the midpoint and endpoint approaches. A research by Bare and Gloria (2006) indicated that the midpoint results are more comprehensive to cover possible environmental interventions, while the endpoint approach may neglect some aspects in deriving the damage indicators. Bare (2010) concluded that the midpoint results can provide analyses in a more scientific way, while the endpoint approach should provide additional support. A recent study by Yi et al. (2011) compared the midpoint and endpoint approaches of LIME (Life Cycle Impact Assessment based on Endpoint Modeling) through a set of solid waste management scenarios and concluded that the results of the midpoint and endpoint are in general consistent except when the primary contributor is not included in the estimated categories. However, it is still unclear if the two approaches can lead to different interpretations.

The construction industry consumes a large volume of materials. It has been reported that buildings account for 40 % of the world's material and energy flows (Horvath 2004). A study (Zabalza Bribián et al. 2011) reported that the civil and construction works are responsible for 60 % of the raw material consumption. On average, the annual production of concrete in the world is around 1 ton per human being (Van den Heede and De Belie 2012; Flower and Sanjayan 2007). The demand for construction materials will continue to grow in developing countries like China, where the building floor area will increase by 30 billion square meters from 2005 to 2020 (Huang et al. 2013). Throughout the life cycle of a building, the construction material stage represents 10–20 % of the energy consumption (Ramesh et al. 2010). Cement as a commonly used construction material accounts for up to 10 % of the weight of concrete and is responsible for 5–7 % of the anthropological carbon emissions (Meyer 2009).

In recent studies, LCA has been conducted to calculate the environmental impact of construction materials (Huntzinger and Eatmon 2009; Huberman and Pearlmutter 2008; Rajagopalan et al. 2010; Landis et al. 2009; Ibbotson and Kara 2013; Collins 2010; Bovea et al. 2009; Hammond and Jones 2008; Bolin and Smith 2011; Menzies 2013; Irfan 2011; Zygomalas et al. 2012; Puettmann et al. 2012), building components (Ortiz et al. 2010; Taborianski and Prado 2012), and the entire building (Zhang et al. 2006; Lee et al. 2009). Nonetheless, the discussion on the midpoint and endpoint approaches is rarely found when a LCIA method is adopted in these studies. Ignoring the difference between the midpoint and the endpoint approaches may result in an inappropriate interpretation on the LCA results.

The present work aims at addressing the differences between the midpoint and endpoint approaches of ReCiPe and using them to analyze the environmental impact of commercial buildings in Hong Kong. In this study, 23 construction materials are examined, covering over 99 % total environmental burden of the materials used in commercial buildings in Hong Kong. Comparison between the midpoint and endpoint based on the normalization results of the selected materials is conducted. The environmental impact of a commercial building in Hong Kong is then analyzed by both the midpoint and endpoint approaches. The difference between the midpoint and endpoint results is investigated. Based on these results, suggestions on when to adopt an endpoint approach and how to interpret the different results from the two approaches are provided. Finally, the limitations and recommendations of the midpoint and endpoint approaches are discussed.

2 Materials and methods

2.1 Impact assessment

The development of ReCiPe was largely due to the need of harmonizing the existing midpoint and endpoint methods to eliminate the barriers of LCIA method selection in LCA design (Goedkoop et al. 2009). ReCiPe is a newly developed LCIA package based on the concepts of CML 2001 and Eco-indicator 99. The name ReCiPe carries twofold meanings: (i) it provides a recipe for the calculation of LCIA; and (ii) it is an acronym of the main contributors which include RIVM and Radboud University, CML and PRé Consultants (Goedkoop et al. 2009). In this study, ReCiPe is selected since the results in both the midpoint and endpoint levels can be provided.

At the midpoint level, 18 impact categories are defined to cover a large variety of impacts. The indicators of impact categories represent the interventions of common concern. Normalization is included in the midpoint by applying a set of midpoint normalization factors obtained from the statistics for the reference year of 2000 (Sleeswijk et al. 2008). Two tiers of normalization factors are available for the European and the World scales, so that the midpoint ReCiPe is capable of calculating the impact in different regional scales. Although weighting factors can be assigned in the midpoint, ReCiPe does not provide a weighting analysis at the midpoint.

At the endpoint level, analysis is available on the impact categories as well as the damage categories. The damage categories describe three AoP which include human health, ecosystems, and resources. Impact categories contribute differently to the three damage categories. In the category of human health, ReCiPe implements the disability-adjusted life years (DALY) which considers the year of life lost and the year of life disabled due to environmental interventions. Damage to ecosystems is described by species lost in a predefined period as a result of emissions to terrestrial, freshwater, and marine systems. Damage to resources is calculated as the economic loss caused by the marginal increase in costs due to the extraction of a resource (Goedkoop et al. 2009). The essence of ReCiPe lies in its ability to link the midpoint and endpoint by means of the endpoint characterization model. The midpoint characterization results are converted into the endpoint characterization results through a set of endpoint characterization factors. The development of connection between the midpoint and the endpoint is the most important outcome of ReCiPe, so that the two approaches are linked as both of them are based on the midpoint characterization results. Normalization and weighting factors are provided in the European and World scales for the three damage categories. A single score can be derived by aggregating the weighting results. Figure 1 shows the connection factors between the elements in impact assessment.

ReCiPe employs a cultural theory (Hofstetter 1998) with three archetypes being used to describe the three groups of considerations and assumptions (Goedkoop et al. 2009). Individualist (I) considers the short-term impact due to the most relevant chemicals. On the other hand, egalitarian (E) is based on the precautionary principle that considers the long-term perspective and involves more risk. Hierarchism (H) is a balanced perspective based on the common policy principles. In addition to I, H, and E, ReCiPe provides another set of weighting factors (A) by averaging the weighting factors of the three perspectives. In this study, the balanced term (H) which is recommended as a default choice is adopted. Since there is no special preference on the weighting factors, the averaged value will be adopted. The ReCiPe Midpoint (H)-World and ReCiPe Endpoint (H)-World H/A are, therefore, used to demonstrate the difference between the midpoint and the endpoint approaches.

2.2 Selection of construction materials

EMSD (2006) studied the environmental impact of construction materials based on the bills of quantities of 28 commercial buildings in Hong Kong. The 20 most influential construction materials according to the single score of Eco-indicator 99 contribute over 99 % to the total environmental impact of all building materials (Table 1). Apart from the top 20 materials, three materials namely cast iron, copper, and paint are included for comparison as they are commonly used in commercial buildings. The results based on the selected materials should, therefore, represent most of the environmental impact of materials in a commercial building in Hong Kong.

A LCI database of Ecoinvent (Frischknecht et al. 2007) is used to simulate majority of the selected materials. The selection of the processes in Ecoinvent becomes a problem when several options are available in the database. Only the common process is chosen to represent the environmental
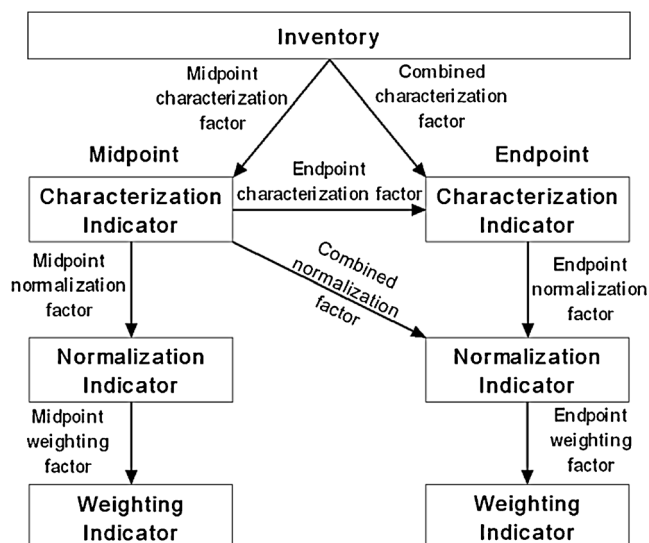
Fig. 1 Connection factors between elements in impact assessment

performance of a material. For instance, five concrete types are provided in Ecoinvent while the most commonly used one

with the strength of B45/35 is adopted. Aluminum is modeled as primary aluminum and secondary aluminum in Ecoinvent, while the production mix of 68 % primary and 32 % secondary aluminum is used to reflect the worldwide production. Three materials viz. galvanized steel, access floor, and precast concrete component are not available in Ecoinvent. Galvanized steel can be modeled by US LCI (NREL 2004). As for access floor, it is modeled by referring to galvanized steel following the assumptions of EMSD (2006). The inventory of precast concrete components was solicited through a field survey (Dong et al. 2013). The LCIA results of the selected materials are generated by SimaPro 7.

2.3 Comparison of structure

This study compares the midpoint and the endpoint LCIA results for individual construction materials as well as the materials used for a commercial building. The comparison begins with a very representative construction material, concrete, due to its large environmental impact (Table 1). All the

Table 1 The selected construction materials and the corresponding processes in LCI database. Contributions to environmental pollution are extracted from EMSD (2006)

Material	Contribution (%)	Data source	Process	FU (kg)
Concrete	23.04	Ecoinvent	Concrete, exacting, with de-icing salt contact, at plant/CH S	1[a]
Rebar	17.56	Ecoinvent	Reinforcing steel, at plant/RER S	1
Plaster, render, and screed	10.38	Ecoinvent	Clay plaster, at plant/CH S	1
Galvanized steel	8.97	US LCI	Galvanized steel sheet, at plant/RNA	1
Tiles	8.17	Ecoinvent	Ceramic tiles, at regional storage/CH S	1
Stones	5.05	Ecoinvent	Natural stone plate, cut, at regional storage/CH S	1
Aluminum	4.9	Ecoinvent	Aluminum, production mix, at plant/RER S	1
Structural steel	4.52	Ecoinvent	Steel, converter, low-alloyed, at plant/RER S	1
Access floor panel	4.36	US LCI	Galvanized steel sheet, at plant/RNA	1
Stainless steel	3.52	Ecoinvent	Steel, converter, chromium steel 18/8, at plant/RER S	1
Plasterboard	2.74	Ecoinvent	Gypsum plaster board, at plant/CH S	1
Glass	1.63	Ecoinvent	Flat glass, coated, at plant/RER S	1
Bricks and blocks	1.22	Ecoinvent	Brick, at plant/RER S	1
Plywood	1.06	Ecoinvent	Plywood, indoor use, at plant/RER S	1[b]
Formwork	1.02	Ecoinvent	Plywood, outdoor use, at plant/RER S	1[b]
Precast items	0.67	Field survey	Precast façade, at plant/CN	1
Acoustic tiles	0.22	Ecoinvent	Gypsum fiber board, at plant/CH S	1
Plastic, rubber, polymer	0.19	Ecoinvent	Polyvinylchloride, at regional storage/RER S	1
Plastic laminate	0.17	Ecoinvent	Polyester resin, unsaturated, at plant/RER S	1
Thermal insulation	0.15	Ecoinvent	Glass wool mat, at plant/CH S	1
Cast iron	–	Ecoinvent	Cast iron, at plant/RER S	1
Copper	–	Ecoinvent	Copper, primary, at refinery/GLO S	1
Paint	–	Ecoinvent	Alkyd paint, white, 60 % in solvent, at plant/RER S	1
Total	99.54			

[a] The default functional unit of concrete in Ecoinvent is 1 m^3. The inventory is converted based on the assumption that density of concrete is 2,300 kg/m^3

[b] The default functional unit of plywood in Ecoinvent is 1 m^3. The inventory is converted based on the assumption that density of plywood is 600 kg/m^3

selected materials are used for the rest of the comparison. The comparison is primarily based on the normalization results as the characterization results cannot be directly compared while the midpoint of ReCiPe provides no analysis on weighting.

To comprehensively interpret the difference caused by the two approaches, the material inventory of a commercial building is analyzed. The results of the building case study can offer an overview of the impact on a building project in real practice due to the switching between the midpoint and endpoint approaches. It can also help improve our understanding beyond the analysis of an individual construction material.

3 Results and discussion

3.1 Interpretation on the LCIA results of concrete

By referring to Table 2, the midpoint approach provides results for the impact categories in two tiers: characterization and normalization. The midpoint characterization results in different units can be difficult to interpret if a LCA participator has insufficient knowledge on the impact categories. For example, the greenhouse gas emissions to produce 1 kg concrete are 0.13 kg CO_2 eq. (carbon dioxide equivalent), though it may not be clear on the consequences of the emissions. The normalization results at the midpoint level can be further analyzed by involving the normalization factors so that the results are normalized to a reference system and hence facilitate the comparison. Climate change has a midpoint normalization factor of 1.45E−4 persons·year/kg (point), derived from the total anthropogenic carbon emissions of 4.18E13 kg CO_2 eq. in 2000 when the world's population was 6,115 million. The value of 1.8E−5 indicates that the production of 1 kg concrete is equivalent to the emission contributed per capita in 9 min. The normalization results sharing the same unit are hence comparable.

The endpoint approach carries out the analysis for both the impact and the damage categories. The characterization results can be compared between the impact categories within the same damage group from the endpoint approach. Damage to human health and ecosystems caused by concrete is mostly attributed to climate change, while fossil depletion is responsible for the damage to resources (Table 2). Although the endpoint approach provides results of various impact categories, the analysis is only conducted for the concerned damage areas, while other aspects are eliminated owing to a lack of knowledge and the unavailability of emission factors (Goedkoop et al. 2009). The impact categories under the human health damage group, e.g., photochemical oxidant formation, particulate matter formation, ionizing radiation, etc. can cause damage to not only the human health but also the ecosystems. On the other hand, acidification, eutrophication, ecotoxicity, and land transformation may also influence

human health. However, since these effects are not clearly understood, they are neglected in the current endpoint LCIA methods. Another deficiency of the endpoint analysis is its incomprehensive coverage of the damage categories which might lead to biases and errors of the final interpretation. The endpoint normalization is based upon the fraction of damage per capita which is the aggregation of several impact categories. Therefore, the endpoint normalization results are apparently smaller than that of the midpoint (Table 2). In the damage assessment level, the endpoint results can be interpreted as an integration of the midpoint results. The endpoint weighting factors of ReCiPe are defined through a panel survey and usually politically concerned. Both the midpoint and endpoint approaches are based on the midpoint characterization results, and a difference may exist in the following steps of normalization, damage assessment and weighting.

Comparison of the normalized scores at the midpoint and endpoint levels (Table 2) reveals that climate change, human toxicity, freshwater eutrophication, and marine ecotoxicity share the same order of magnitude at the midpoint level, while the normalized scores of these impact categories at the endpoint level differ by for example 8 orders of magnitude between climate change (human health) and marine ecotoxicity. The inconsistent normalized scores are attributed to the different normalization factors under the two approaches. The midpoint normalization factor is 1.45E−04 of climate change (human health) and 4.14E−04 of marine ecotoxicity, whereas the combined normalization factor (product of endpoint characterization and endpoint normalization) is 1.04E−04 of climate change (human health) and 4.89E−11 of marine ecotoxicity. This suggests that the midpoint and endpoint approaches can lead to inconsistent results of materials which are dominated by different impact categories.

It can be realized that the calculation process in LCIA is in fact a way to extract information from abundant data so that the results can be easily interpreted in either a single score or by means of damage indicators. The emission inventory is aggregated to the indicators of impact categories which are further combined to derive the single score by applying the characterization factors, normalization factors, and weighting factors. A good LCIA method should be able to provide those factors in a scientific way, e.g., through the fate modeling, numerical modeling, data mining, questionnaire survey, Delphi method, etc., so that any artificial influence can be minimized. A schematic diagram is given in Fig. 2 to illustrate the data extraction process in LCIA. The pyramid shape represents the data loss from LCI to a single score. The inventory of environmental interventions includes all the recognized emissions caused by a product or process. By performing LCIA, the results become less comprehensive but more concise. The endpoint approach hence provides a more concise way to interpret the LCA results.

Table 2 LCIA results of 1 kg concrete using the midpoint and endpoint approaches of ReCiPe with the unit of normalization and weighting results being point (pt)

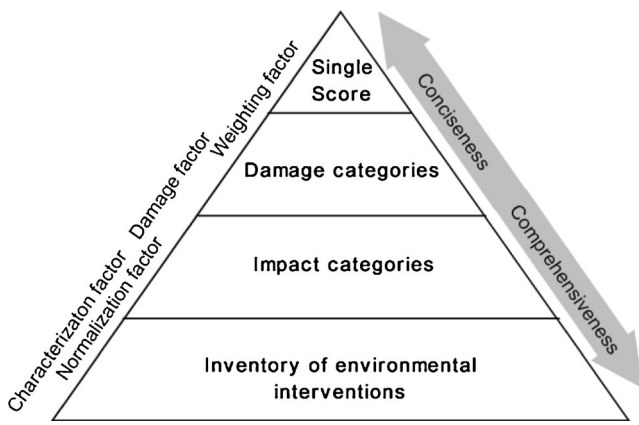| Damage categories	Impact categories	Midpoint		Endpoint						
		Characterization	Normalization (pt)	Characterization	Damage	Normalization (pt)	Damage (pt)	Weighting (pt)	Damage (pt)	Score (pt)
Human health	Climate change: human health	1.3E−01 kg CO_2 eq.	1.8E−05	1.8E−07	2.1E−07 DALY	1.3E−05	1.5E−05	5.2E−03	6.1E−03	8.5E−03
	Ozone depletion	4.2E−09 kg CFC-11 eq.	1.1E−07	1.1E−11		8.2E−10		3.3E−07		
	Human toxicity	1.0E−02 kg 1,4-DB eq.	8.9E−05	7.3E−09		5.4E−07		2.2E−04		
	Photochemical oxidant formation	2.6E−04 kg NMVOC	5.4E−06	1.0E−11		7.6E−10		3.1E−07		
	Particulate matter formation	8.9E−05 kg PM10 eq.	6.3E−06	2.3E−08		1.7E−06		6.9E−04		
	Ionizing radiation	1.4E−02 kg U235 eq.	1.1E−05	2.3E−10		1.7E−08		6.8E−06		
Ecosystem	Climate change: ecosystems	1.3E−01 kg CO_2 eq.	1.8E−05	9.9E−10	1.0E−09 Species year	1.2E−06	1.2E−06	4.6E−04	4.9E−04	
	Terrestrial acidification	2.2E−04 kg SO_2 eq.	5.7E−06	1.3E−12		1.5E−09		5.8E−07		
	Freshwater eutrophication	6.8E−06 kg P eq.	2.3E−05	3.0E−13		3.5E−10		1.4E−07		
	Marine eutrophication	1.0E−05 kg N eq.	1.4E−06	–		–		–		
	Terrestrial ecotoxicity	3.0E−06 kg 1,4-DB eq.	4.6E−07	3.8E−13		4.5E−10		1.8E−07		
	Freshwater ecotoxicity	1.4E−04 kg 1,4-DB eq.	3.3E−05	3.7E−14		4.4E−11		1.7E−08		
	Marine ecotoxicity	1.5E−04 kg 1,4-DB eq.	6.3E−05	1.2E−16		1.4E−13		5.7E−11		
	Agricultural land occupation	9.2E−04 m^2a	1.7E−07	1.0E−11		1.2E−08		4.8E−06		
	Urban land occupation	7.4E−04 m^2a	9.6E−07	1.4E−11		1.7E−08		6.7E−06		
	Natural land transformation	1.4E−05 m^2	1.1E−06	2.3E−11		2.7E−08		1.1E−05		
Resources	Water depletion	1.7E−03 m^3	0.0E+00	–	2.0E−01 $	–	9.3E−06	–	1.9E−03	
	Metal depletion	2.3E−03 kg Fe eq.	5.1E−06	1.6E−04		7.4E−09		1.5E−06		
	Fossil depletion	1.3E−02 kg oil eq.	9.3E−06	2.0E−01		9.2E−06		1.8E−03		

Fig. 2 Schematic illustration of LCIA procedures

3.2 Results of selected materials

The results of the selected construction materials are studied in this section. Contributions from the impact categories to the endpoint single score are presented in Fig. 3, where four impact categories are found to be the most influential to the endpoint single score, viz. climate change, human toxicity, particulate matter formation, and fossil depletion. In addition, agricultural land occupation caused by plywood has a large impact on the single score as well.

Figure 4 gives the ranking of impact categories based on the ratio between the combined normalization factors and the midpoint normalization factors (as defined in Fig. 1). It is found that for most of the cases, the midpoint normalization factors are larger than the combined normalization factors, suggesting that the midpoint normalization results are greater

than the endpoint normalization results (Table 2). An impact category with a smaller ratio indicates that the midpoint normalization result receives a greater emphasis than the endpoint normalization result.

In Fig. 5, the normalization results of impact categories are aggregated to normalized scores that are compared between the selected materials. In general, the midpoint agrees with the endpoint, though disagreement can still be found. For example, the normalized score of paint is larger than that of structural steel in the endpoint while the midpoint results of the two materials are in a reverse order. This is because the midpoint normalized score of structural steel is dominated by marine ecotoxicity, freshwater ecotoxicity, and metal depletion. However, the combined normalization factors of the three impact categories are comparatively small which are ranked 13th, 14th, and 10th among the 18 impact categories. As a result, the difference caused by the three impact categories becomes negligible in the endpoint. On the other hand, the great combined normalization factor of fossil depletion with the 2nd rank can magnify the difference at endpoint, resulting in a larger endpoint normalized score of paint than that of structure steel. The magnifying effect of fossil depletion on the endpoint normalized score can also be observed when comparing other materials, e.g., "plastic, rubber, polymer" and "tiles". As shown in Fig. 4, the ratio of fossil depletion is the greatest among the impact categories, indicating the high normalized scores of fossil depletion at endpoint. Climate change, fossil depletion, and particulate matter formation of which the ratios are comparatively large can contribute significantly to the endpoint single score. This suggests that the materials being dominated by the three categories may demonstrate a greater
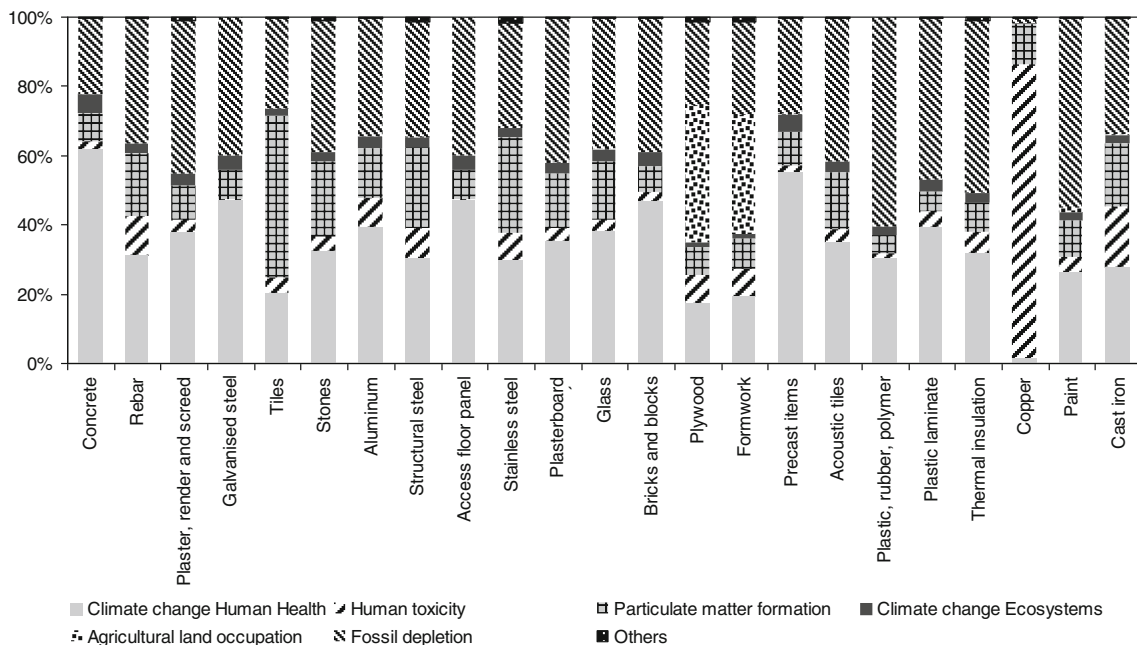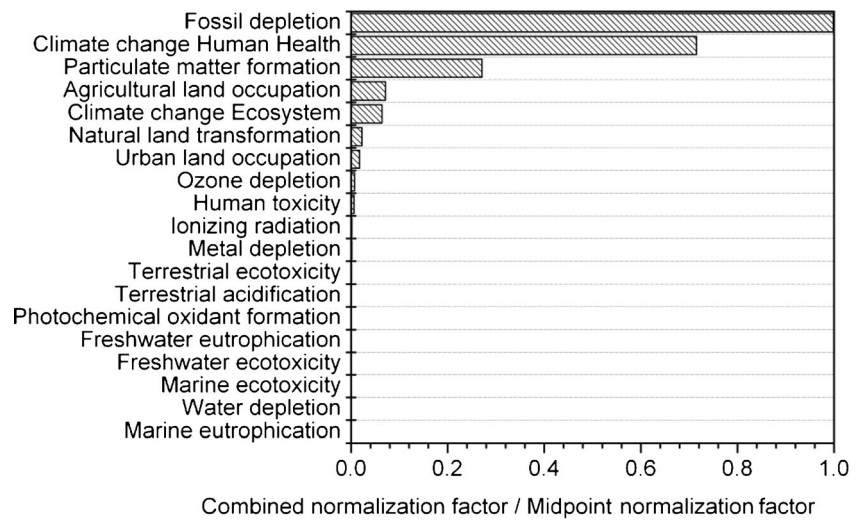

Fig. 3 Contributions from impact categories toward endpoint single score

environmental influence according to the endpoint single score as compared with those materials which are dominated by other impact categories.

The ranking of materials as given in Fig. 5 is based on the averaged impact scores. However, when taking uncertainties into account, the ranking may be rearranged. In order to examine the influence of uncertainty, a Monte Carlo analysis is carried out for structural steel and paint. The model is run for 500 times. It is found that the midpoint normalized score of paint has a standard deviation of 4.97E−3 and a mean of 3.20E−2. The average midpoint normalized score of a nearby point rebar is 3.01E−2 (Fig. 5). In that case 3.20E−2 to 4.97E−3<3.01E−2, indicating paint has more than 16 % possibility to be ranked lower than rebar in terms of the midpoint normalized score. Similarly, the orders of structural steel and plastic laminate may be reversed at the midpoint.

In Table 3, the rankings of impact categories are compared for the selected materials. The ranking of impact categories presents completely different features between the midpoint and the endpoint approaches. In the midpoint, human toxicity, marine ecotoxicity, and freshwater ecotoxicity are the most contributive impact categories for most of the selected materials. Nonetheless, the endpoint results show that fossil depletion, climate change (human health), and particulate matter formation are more influential. This can be explained by Fig. 4, in which the ratios of the three categories are larger than the others. The different rankings of scenarios and impact categories as shown in Fig. 5 and Table 3 imply that the implementation of the midpoint and endpoint approaches can lead to different interpretations in and after the normalization step when more than one impact categories are considered.

Fig. 5 Comparison of the total
environmental performance of the
selected materials based on
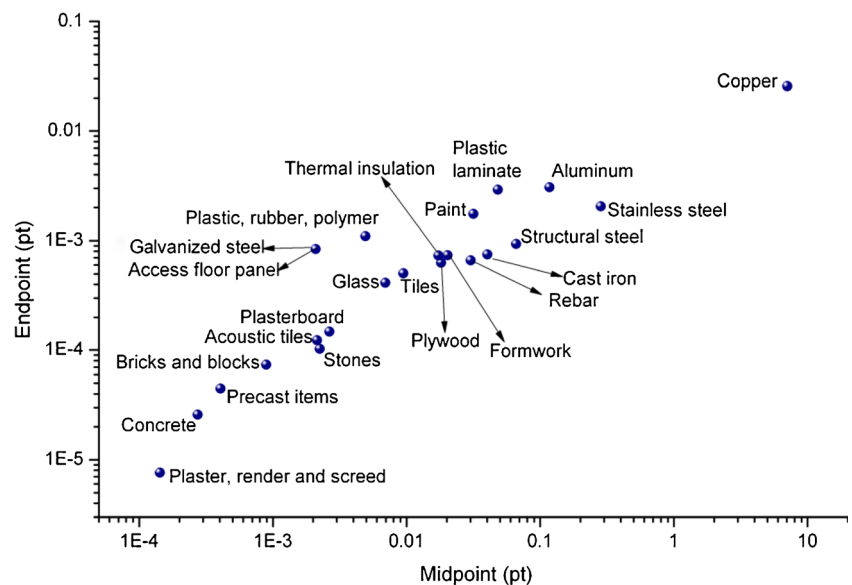normalization results (functional
unit—1 kg)

Table 3 Ranking of impact categories for construction materials based on normalization results per kilogram construction material. Contributions of impact categories are shown (normalization results are equally weighted)

Material	Approach	1st		2nd		3rd	
Concrete	Midpoint	HT	31 %	MET	22 %	FET	11 %
	Endpoint	CC(HH)	51 %	FD	36 %	PMF	7 %
Rebar	Midpoint	MET	31 %	HT	30 %	FET	17 %
	Endpoint	FD	53 %	CC(HH)	23 %	PMF	13 %
Plaster, render, and screed	Midpoint	MET	30 %	HT	23 %	FET	12 %
	Endpoint	FD	61 %	CC(HH)	26 %	PMF	7 %
Galvanized steel	Midpoint	FET	48 %	FD	19 %	HT	17 %
	Endpoint	FD	57 %	CC(HH)	34 %	PMF	6 %
Tiles	Midpoint	HT	32 %	MET	25 %	FET	13 %
	Endpoint	FD	41 %	PMF	37 %	CC(HH)	16 %
Stones	Midpoint	MET	25 %	HT	24 %	IR	13 %
	Endpoint	FD	55 %	CC(HH)	23 %	PMF	15 %
Aluminum	Midpoint	MET	35 %	HT	28 %	FET	19 %
	Endpoint	FD	51 %	CC(HH)	29 %	PMF	11 %
Structural steel	Midpoint	MET	38 %	FET	21 %	MD	16 %
	Endpoint	FD	50 %	CC(HH)	23 %	PMF	18 %
Access floor panel	Midpoint	FET	48 %	FD	19 %	HT	17 %
	Endpoint	FD	57 %	CC(HH)	34 %	PMF	6 %
Stainless steel	Midpoint	MET	50 %	FET	27 %	MD	11 %
	Endpoint	FD	46 %	CC(HH)	22 %	PMF	21 %
Plasterboard	Midpoint	MET	31 %	HT	25 %	FET	15 %
	Endpoint	FD	59 %	CC(HH)	25 %	PMF	11 %
Glass	Midpoint	HT	26 %	MET	24 %	FET	14 %
	Endpoint	FD	55 %	CC(HH)	27 %	PMF	12 %
Bricks and blocks	Midpoint	HT	28 %	MET	25 %	FET	14 %
	Endpoint	FD	56 %	CC(HH)	34 %	PMF	5 %
Plywood	Midpoint	HT	38 %	MET	17 %	ALO	15 %
	Endpoint	FD	39 %	ALO	32 %	CC(HH)	14 %
Formwork	Midpoint	HT	38 %	MET	18 %	ALO	14 %
	Endpoint	FD	42 %	ALO	27 %	CC(HH)	15 %
Precast items	Midpoint	HT	30 %	MET	19 %	FET	10 %
	Endpoint	FD	43 %	CC(HH)	43 %	PMF	8 %
Acoustic tiles	Midpoint	MET	31 %	HT	25 %	FET	15 %
	Endpoint	FD	59 %	CC(HH)	25 %	PMF	11 %
Plastic, rubber, polymer	Midpoint	HT	30 %	FD	16 %	MET	15 %
	Endpoint	FD	75 %	CC(HH)	19 %	PMF	3 %
Plastic laminate	Midpoint	HT	32 %	MET	28 %	FET	14 %
	Endpoint	FD	64 %	CC(HH)	27 %	PMF	4 %
Thermal insulation	Midpoint	HT	28 %	MET	24 %	FET	14 %
	Endpoint	FD	66 %	CC(HH)	21 %	PMF	6 %
Copper	Midpoint	HT	50 %	MET	27 %	FET	12 %
	Endpoint	HT	84 %	PMF	11 %	FD	3 %
Paint	Midpoint	MET	28 %	HT	26 %	FET	17 %
	Endpoint	FD	71 %	CC(HH)	17 %	PMF	7 %
Cast iron	Midpoint	HT	41 %	MET	28 %	FET	15 %
	Endpoint	FD	50 %	CC(HH)	20 %	PMF	14 %

ALO agricultural land occupation, *CC(HH)* climate change (human health), *FD* fossil depletion, *FE* freshwater eutrophication, *FET* freshwater ecotoxicity, *HT* human toxicity, *MD* metal depletion, *MET* marine ecotoxicity, *PMF* particulate matter formation

3.3 Results of a commercial building

The studied building is a 30-storey commercial building in Hong Kong. The building provides 43,210 m^2 of construction floor area (CFA) (Zhang et al. 2013). The results of the building can provide further insights when dealing with real case study. The key construction materials in the commercial building are given in Table 4. It should be noted that only the materials listed in Table 1 are analyzed, while the other materials are ignored due to their relatively insignificant impact. The LCIA results of rebar are used to represent the environmental impact of steel in the studied building.

The comparison is conducted at the normalization level. As shown in Fig. 6, there is no obvious relationship between the midpoint and the endpoint results in terms of the ranking of impact categories. This is consistent with the observation in the previous sections for individual materials. For instance, freshwater ecotoxicity contributes significantly in the midpoint approach, while it receives the lowest rank in the endpoint approach. Similar observations can be found for the categories of fossil depletion, freshwater eutrophication, particulate matter, etc. The underlying rationale behind this disagreement is the effects of the midpoint normalization factors and the combined normalization factors, which can be explained by the different ratios in Fig. 4.

A further step is to study the contributions from individual materials to the total environmental impact using the midpoint and endpoint approaches (Fig. 7). The results show that the contributive percentage of concrete is larger in the endpoint than in the midpoint. In contrast, steel accounts more environmental impact in the midpoint than in the endpoint. This is attributed to the different values of normalization factors of the two approaches. Climate change (human health) ranks high in the endpoint while low in the midpoint, corresponding to the larger contribution of concrete in the endpoint. It should be noted that in Table 1, concrete has been estimated as the most contributive material to the environmental impact of a building, while in Fig. 7, steel is responsible for more impact. This is because Table 1 divides the steel types into rebar, galvanized steel, structural steel, and stainless steel, while Fig. 7 considers the aggregated effects of all steel types. The results in Figs. 6 and 7 indicate that precaution should be paid before conducting a LCIA analysis since an interpretation based on the midpoint and endpoint results can be very different.

ISO 14040 points out that no scientific basis is available for weighting. The methodology to define the weighting factors remains controversial as different LCIA methods may adopt distinctive ways to quantify the weighting factors. Eco-indicator 99 (the predecessor of ReCiPe endpoint method) constructs the weighting factors through a panel survey with 365 interested persons (Goedkoop et al. 1999). The life cycle impact assessment method (LIME) in Japan develops the weighting factors by conjoint analysis based on 1,000 responses for its second version LIME2 (Itsubo et al. 2012). In ReCiPe, weighting factors are assigned by a similar way to Eco-indicator 99. The weighting is not provided in the level of impact categories but is only applicable to the endpoint damage categories. The endpoint approach defines the weighting factors for the three time perspectives as well as their average. The emphasis on damage categories shifts from human health for short-term perspective (I) to ecosystems for long-term perspective (E). The human health and ecosystems share the same weighting factor in the averaged set (A). Among the three damage categories, weighting factor of resources is the smallest. The choice among the weighting factors should hence depend on which damage category is mostly concerned in the LCA study.

The ReCiPe Endpoint (H)-World H/A is used in the above analysis. Here, the effects of three weighting methods are compared by calculating the contributions from the damage categories to a single score for the studied building. As observed in Fig. 8, the single score being calculated by the equal weighting factors is apparently higher than the single scores from other weighting methods. Therefore, the weighting factors would not only determine the contributions of the damage categories toward the total impact but they could also influence the value of the single score.

3.4 Difference between midpoint and endpoint

This study reveals that if the ranking of construction materials is calculated for an individual category, the midpoint and the endpoint are consistent in ReCiPe. Consequently, the two approaches can lead to the same ranking if the LCA study is performed for individual impact categories.

If all the impact categories are considered, the ranking of construction materials is in general consistent. However, differences can still be found when the materials are dominated by distinct impact categories. By examining the normalization results of impact categories, the endpoint results are smaller than the midpoint results, except for the category of fossil depletion. In the endpoint, fossil depletion, climate change, and particulate matter formation are emphasized by applying a great value of combined normalization factors, while in the midpoint, the categories of toxicity become more important. This can lead to a risk of steering toward the desired results. As if when one option is favored, the approach with the best

Table 4 Major materials of a commercial building in Hong Kong with the data calculated from Zhang et al. (2013)

Material	Quantity (ton)
Concrete	61,074
Steel	6,126
Glass	190
Timber	96
Aluminum	67

Fig. 6 Comparison between normalization results of the case building using midpoint and endpoint approaches based on the resource use for the commercial building
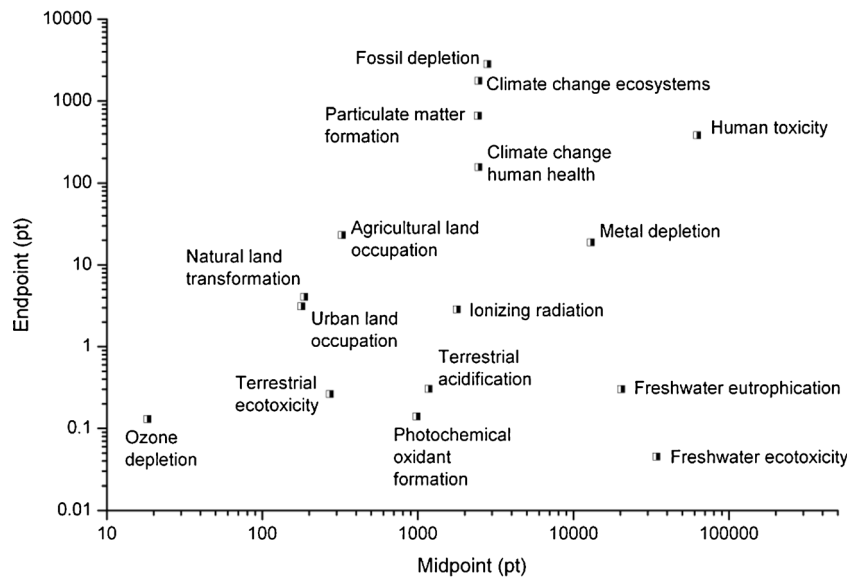
outcomes for this option could become the choice. For example, when selecting materials for a building construction project, the contractor may prefer the endpoint approach if the selected materials are dominated by toxicity or ecotoxicity. To prevent any subjective adoption of the midpoint and endpoint approaches, it is suggested that the estimation should be given in the individual impact categories in addition to an impact score, following the requirements given in ISO 14044.

The ranking of impact categories can be very different when using the midpoint and endpoint approaches of ReCiPe. This is valid for the selected construction materials and the commercial building. When comparing the importance of impact categories, the midpoint approach is suggested if there is no special request on the damage assessment, as the midpoint approach should be able to generate more reliable results. If the endpoint characterization results are used, the midpoint characterization results should also be provided for reference. If the endpoint single score is used, it should according to ISO (2006a) be complemented with the underlying midpoint results without using weighting.
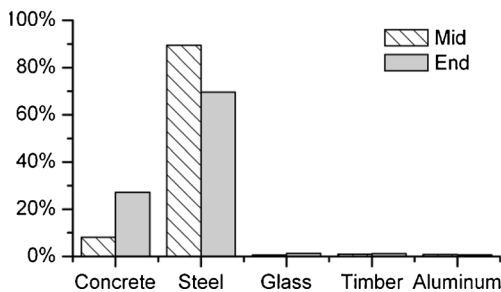
The midpoint and endpoint may lead to different interpretations if the contributions from the subprocesses to the total environmental performance of commercial buildings are analyzed. This can cause a problem when LCA is used to detect the hot spots. For instance, the contribution of concrete is more significant in the endpoint than in the midpoint. To reduce the environmental impact of a commercial building, the contractor may wish to use more cementitious substitute (e.g., fly ash, blast furnace slag, silica fume, etc.) for concrete if the endpoint score is referred. Nevertheless, more effort may be paid to adopt recycled steel when the midpoint approach is used. To resolve this problem, participators should define the important impact categories clearly in the goal and scope definition stage. In other words, it should be determined in what impact categories the hot spots will be detected. For commercial buildings in Hong Kong, if the concerned categories are climate change and energy consumption in general, the contributions of materials toward climate change and
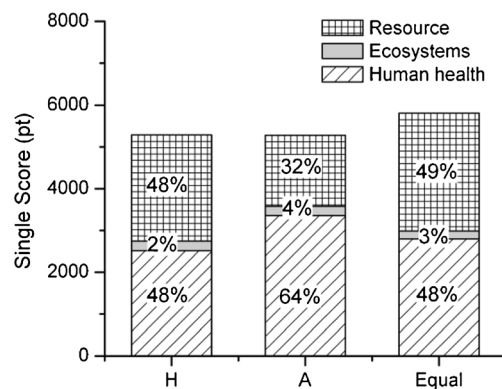
Fig. 7 The contribution analysis of the environmental impact of construction materials of the case building using midpoint and endpoint approaches based on the resource use for the commercial building (normalization results are equally weighted)

Fig. 8 The contribution from damage categories to single score using different weighting factors based on the resource use for the commercial building (H: balanced-term; A: averaged perspective; Equal: equally weighted)

energy consumption can hence be used to identify the hot spots.

As pointed out in ISO 14040 / 44, the weighting is based on value choices with no scientific basis. The implementation of a single score is hereby limited. The results in this study indicate that the weighting factors can change the single score of the studied building. The single score is larger if the damage categories are equally weighted. The choice among the weighting factors should depend on which damage category is mostly concerned in the LCA study.

Under most PCRs, the evaluation stops at the midpoint. This is also true for the PCR of construction works (EN 15804:2012). As discussed above, the midpoint is more reliable while the endpoint could lead to larger uncertainties. The implementation of the midpoint seems to be a wise choice for most cases. However, the endpoint approach has advantages as it can provide easy-to-understand results by considering the damage. The implementation of the endpoint approach should be encouraged when environmental LCA is integrated with life cycle costing (LCC) (Hunkeler et al. 2008) and social LCA (SLCA) (UNEP 2009) in a life cycle sustainability assessment (LCSA) (UNEP 2012). The indicator of human health (DALY) can be directly used to assess the social impact. Moreover, the unit of resources is monetary-based, so that the result of resources can be substituted to LCC as externalities.

One should note that the above discussion is based on ReCiPe. For the LCA studies using other methods such as CML, Eco-indicator 99, TRACI, EPS (Steen 1999), or IMPACT 2002+ (Jolliet et al. 2003), the situation can be rather different. For example, if CML is applied as the midpoint method while Eco-indicator 99 is used as the endpoint method, the results will vary at the characterization level rendering them incomparable. If both the midpoint and endpoint results are desired in a LCA study, the LCIA methods with both the midpoint and endpoint approaches like ReCiPe are strongly recommended.

3.5 Limitation and recommendations

LCIA conducts analyses to extract essential information from an inventory of environmental interventions. In this process, part of information is lost while the LCIA results are largely determined by a set of factors (characterization factors, normalization factors, etc.). The way to evaluate the environmental performance of a product is schematized at levels of midpoint and endpoint in LCIA. The endpoint approach provides results with higher degree of interpretation but larger uncertainty. On the other hand, the midpoint approach is more reliable but does not give information of damages. The midpoint and endpoint are only two representative sections along the cause-effect chain. There could be more tiers and one example is the concentration of pollutants which can be

derived by fate modeling. The midpoint approach provides comprehensive results covering many impact categories, while the endpoint gives concise information of damages in three AoP.

In LCIA, the factors are defined based on the current knowledge of the impact categories and may not reflect the real situation. For example, the eutrophication process is calculated in the LCIA with indicators of nutrients in the midpoint and potentially disappeared fraction of species in the endpoint. The damage factor of freshwater eutrophication is obtained by a regression analysis between species loss and phosphorus concentration. However, eutrophication in aquatic system is actually determined by many complex hydrodynamic (e.g., flow velocity, turbulence, stability) and biochemical (e.g., intake by algae and other aquatic lives) processes, which have not been fully understood. Thus, the eutrophication process cannot be precisely modeled by the damage factor as defined in LCIA.

LCA is a comparison tool that examines the environmental impacts of products by considering the potential exposure rather than the actual exposure. There are other assessment tools that focus on the actual exposure, such as risk assessment and environmental impact assessment. These assessment techniques need extra effort (e.g., field monitoring, computational fluid dynamics modeling, data mining, etc.). The advantage of LCA lies in its ability to describe the studied system with a holistic and easy-to-use LCIA method. LCA deals with the whole life cycle chain of products, which is usually not covered by other assessment tools. The environmental impacts in LCA are calculated from a set of well-defined factors, which help simplify the studied problem and accelerate the analysis.

LCA can be integrated with other techniques to provide more accurate analysis. One example is to integrate it with geographic information system (GIS) to provide detailed spatial analysis (Geyer et al. 2010). This, however, requires more effort to collect site-specific data. In the construction industry, the integration of LCA with building information modeling (BIM) has been attempted by Kulahcioglu et al. (2012).

4 Conclusions

The midpoint and the endpoint approaches can provide assessment at different levels resulting in distinctive interpretations. This study has examined the implementation of the midpoint and endpoint approaches of ReCiPe by analyzing 23 construction materials as well as a commercial building. The results in this study indicate that the difference in the two approaches can be detected when several impact categories are taken into consideration. The rankings of impact categories demonstrate completely different features due to the effects of midpoint normalization factors and combined

normalization factors. The ranking of materials is slightly different under the two approaches when the materials are dominated by different impact categories. Uncertainty can influence the rankings of materials with similar impact scores. In the case study of a commercial building in Hong Kong, the contribution from concrete is larger in the endpoint approach due to the greater factor value of climate change (human health) in the endpoint approach. In terms of weighting, the single score and contributions from damage categories may vary when different weighting factors are used.

The midpoint approach is able to provide analysis for a set of impact categories despite the results are difficult to interpret. The endpoint approach includes the damage assessment and introduces more uncertainties to the results. The midpoint approach is in general preferred since it can provide reliable assessment, while the endpoint approach gives additional information of damage with a higher degree of interpretation. In the LCIA calculation, the original information is whittled down through the calculation in LCIA from LCI to a single score and the essential information of high concern is extracted. Compared with midpoint results, endpoint results are less comprehensive but more concise.

Suggestions are provided to help designers interpret results from the two approaches, in particular, for the assessment of commercial buildings in Hong Kong. Since the midpoint and endpoint approaches can lead to different outcomes, any subjective adoption to steer toward the desired results should be prevented. The critical impact categories, in which the environmental performance is compared and analyzed, should be identified in the goal and scope definition. Characterization results per impact category should be given when the endpoint approach is used. If a single score is reported, it is mandatory to supply this result with the underlying midpoint LCIA results. The endpoint weighting factors should be properly selected to reflect the importance of AoPs. These suggestions are proposed based on ReCiPe and may not be applicable to methods with entirely different concepts such as the midpoint by CML and the endpoint by Eco-indicator 99. When an endpoint result is asked for, the LCIA methods with both midpoint and endpoint analyses like ReCiPe are strongly recommended.

References

Amani P, Schiefer G (2011) Review on suitability of available LCIA methodologies for assessing environmental impact of the food sector. Int J Food Syst Dyn 2(2):194–206

Bare JC (2010) Life cycle impact assessment research developments and needs. Clean Techn Environ Policy 12(4):341–351

Bare JC, Gloria TP (2006) Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches. Environ Sci Technol 40(4):1104–1113

Bare JC, Hofstetter P, Pennington DW, de Haes HAU (2000) Midpoints versus endpoints: the sacrifices and benefits. Int J Life Cycle Assess 5(6):319–326

Berger M, Finkbeiner M (2011) Correlation analysis of life cycle impact assessment indicators measuring resource use. Int J Life Cycle Assess 16(1):74–81

Bolin CA, Smith ST (2011) Life cycle assessment of borate-treated lumber with comparison to galvanized steel framing. J Clean Prod 19(6):630–639

Bovea MD, Diaz-Albo E, Gallardo A, Colomer FJ, Serrano J (2009) Environmental performance of ceramic tiles: improvement proposals. Mater Des 31:35–41

Brent AC, Hietkamp S (2003) Comparative evaluation of life cycle impact assessment methods with a South African case study. Int J Life Cycle Assess 8(1):27–38

Cavalett O, Chagas MF, Seabra JEA, Bonomi A (2013) Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. Int J Life Cycle Assess 18(3):647–658

CEN (2012) BS EN 15804:2012 Sustainability of construction works—environmental product declarations—core rules for the product category of construction products. European Standard. European Committee for Standardization (CEN)

Collins F (2010) Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint. Int J Life Cycle Assess 15(6):549–556

Dong YH, Wong CTC, Ng ST, Wong JMW (2013) Life cycle assessment of precast concrete units. Paper presented at the International Conference on Civil, Environmental and Architectural Engineering Madrid, Spain, March 28–29, 2013

Dreyer LC, Niemann AL, Hauschild MZ (2003) Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. Int J Life Cycle Assess 8(4):191–200

EMSD (2006) Consultancy study on life cycle energy analysis of building construction. Electrical and Mechanical Services Department, Government of Hong Kong Special Administrative Region, Hong Kong

EPA (2003) Tool for the reduction and assessment of chemical and other environmental impacts (TRACI): user's guide and system documentation. National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manag 91(1):1–21

Flower DJM, Sanjayan JG (2007) Green house gas emissions due to concrete manufacture. Int J Life Cycle Assess 12(5):282–288

Frischknecht R, Jungbluth N, Althaus H, Doka G, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M (2007) Overview and methodology. Ecoinvent report. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Geyer R, Stoms DM, Lindner JP, Davis FW, Wittstock B (2010) Coupling GIS and LCA for biodiversity assessments of land use. Int J Life Cycle Assess 15(5):454–467

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R (2009) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: characterisation, first edition. Ministerie van Volkshuisvesting, Ruimtleijke Ordening en Milieubeheer, The Netherlands

Goedkoop M, Spriensma R, van Volkshuisvesting M, en Milieubeheer RO, Communicatie CD (1999) The Eco-indicator 99: a damage oriented method for life cycle impact assessment. Ministerie van

Volkshuisvesting, Ruimtlijke Ordening en Milieubeheer, The Netherlands

Guinée J (ed) (2001) Life cycle assessment: an operational guide to the ISO standards. Center of Environmental Science - Leiden University (CML), The Netherlands

Hammond GP, Jones CI (2008) Embodied energy and carbon in construction materials. Energy 161(2):87–98

Heijungs R, Goedkoop M, Struijs J, Effting S, Sevenster M, Huppes G (2003) Towards a life cycle impact assessment method which comprises category indicators at the midpoint and the endpoint level. Report of the first project phase: design of the new method VROM report

Hofstetter P (1998) Perspectives in life cycle impact assessment: a structured approach to combine models of the technosphere, ecosphere, and valuesphere. Doctoral Thesis, Swiss Federal Institute of Technology Zurich, Zurich

Horvath A (2004) Construction materials and the environment. Annu Rev Environ Resour 29:181–204

Huang T, Shi F, Tanikawa H, Fei J, Han J (2013) Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. Resour Conserv Recycl 72:91–101

Huberman N, Pearlmutter D (2008) A life-cycle energy analysis of building materials in the Negev desert. Energy Build 40(5):837–848

Hunkeler D, Lichtenvort K, Rebitzer G, Ciroth A, Europe S (2008) Environmental life cycle costing. SETAC, New York

Huntzinger DN, Eatmon TD (2009) A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. J Clean Prod 17:668–675

Ibbotson S, Kara S (2013) LCA case study. Part 1: cradle-to-grave environmental footprint analysis of composites and stainless steel I-beams. Int J Life Cycle Assess 18(1):208–217

ILCD (2011) Recommendations for life cycle impact assessment in the European context-based on existing environmental impact assessment models and factors. Institute for Environment and Sustainability, Joint Research Centre, European Commission

Irfan M (2011) Carbon footprint of ready mix concrete and the role of environmental classification systems. Master Thesis, Chalmers University of Technology, Göteborg, Sweden

ISO (2006a) ISO 14044:2006 Environmental management—life cycle assessment—requirements and guidelines. International Organization for Standardization, Geneva, Switzerland

ISO (2006b) ISO 14040:2006 Environmental management—life cycle assessment—principles and framework. International Organization for Standardization, Geneva, Switzerland

ISO (2010) BS EN ISO 14025:2010 Environmental labels and declarations—type III environmental declarations—principles and procedures. International Organization for Standardization, Geneva, Switzerland

Itsubo N, Sakagami M, Kuriyama K, Inaba A (2012) Statistical analysis for the development of national average weighting factors—visualization of the variability between each individual's environmental thoughts. Int J Life Cycle Assess 17(4): 488–498

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8(6):324–330

Kulahcioglu T, Dang J, Toklu C (2012) A 3D analyzer for BIM-enabled life cycle assessment of the whole process of construction. HVAC&R Res 18(1–2):283–293

Landis AE, Bilec MM, Rajagopalan N (2009) Life cycle assessment for evaluating green products and materials. Paper presented at the US-Japan Workshop on LCA of Sustainable Infrastructure Materials, Sapporo, Japan, October 21–22

Landis AE, Theis TL (2008) Comparison of life cycle impact assessment tools in the case of biofuels. Paper presented at the IEEE

international symposium on electronics and the environment, San Francisco, CA, May 19–22

Lee K, Tae S, Shin S (2009) Development of a life cycle assessment program for building (SUSB-LCA) in South Korea. Renew Sust Energy Rev 13(8):1994–2002

Menzies GF (2013) Life cycle assessment of timber, modified timber and aluminium-clad timber windows. Institute for Building and Urban Design, Heriot Watt University, Edinburgh

Meyer C (2009) The greening of the concrete industry. Cem Concr Compos 31(8):601–605

Monteiro H, Freire F (2012) Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. Energy Build 47:572–583

Notarnicola B, Huppes G, van den Berg NW (1998) Evaluating options in LCA: the emergence of conflicting paradigms for impact assessment and evaluation. Int J Life Cycle Assess 3(5):289–300

NREL (2004) U.S. LCI database project—user's guide. National Renewable Energy Laboratory, Golden, Colorado

Ortiz O, Pasqualino JC, Díez G, Castells F (2010) The environmental impact of the construction phase: an application to composite walls from a life cycle perspective. Resour Conserv Recycl 54(11):832–840

Pennington D, Potting J, Finnveden G, Lindeijer E, Jolliet O, Rydberg T, Rebitzer G (2004) Life cycle assessment. Part 2: current impact assessment practice. Environ Int 30(5):721–739

Pizzol M, Christensen P, Schmidt J, Thomsen M (2011) Impacts of metals on human health: a comparison between nine different methodologies for life cycle impact assessment(LCIA). J Clean Prod 19(6–7):646–656

Puettmann ME, Oneil E, Wilson JB, Johnson LR (2012) Cradle to gate life cycle assessment of softwood plywood production from the Southeast. CORRIM Report Update

Rajagopalan N, Bilec MM, Landis AE (2010) Residential life cycle assessment modeling: comparative case study of insulating concrete forms and traditional building materials. J Green Build 5(3):95–106

Ramesh T, Prakash R, Shukla K (2010) Life cycle energy analysis of buildings: an overview. Energy Build 42(10):1592–1600

Renou S, Thomas J, Aoustin E, Pons M (2008) Influence of impact assessment methods in wastewater treatment LCA. J Clean Prod 16(10):1098–1105

Schulze C, Jödicke A, Scheringer M, Margni M, Jolliet O, Hungerbühler K, Matthies M (2001) Comparison of different life—cycle impact assessment methods for aquatic ecotoxicity. Environ Toxicol Chem 20(9):2122–2132

Sleeswijk AW, Van Oers LFCM, Guinée JB, Struijs J, Huijbregts MAJ (2008) Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. Sci Total Environ 390(1):227–240

Steen B (1999) A systematic approach to environmental priority strategies in product development(EPS). Version 2000—general system characteristics. Centre for Environmental Assessment of Products and Material Systems, Gothenburg

Taborianski VM, Prado RT (2012) Methodology of CO₂ emission evaluation in the life cycle of office building façades. Environ Impact Assess Rev 33(1):41–47

UNEP (2009) Guidelines for social life cycle assessment of products. United Nations Environmental Programme, Paris, France

UNEP (2012) Towards a life cycle sustainability assessment—making informed choices on products. United Nations Environmental Programme, Paris

Van den Heede P, De Belie N (2012) Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: literature review and theoretical calculations. Cem Concr Compos 34(4):431–442

Yi S, Kurisu KH, Hanaki K (2011) Life cycle impact assessment and interpretation of municipal solid waste management scenarios based on the midpoint and endpoint approaches. Int J Life Cycle Assess 16(7):652–668

Zabalza Bribián I, Valero Capilla A, Aranda Usón A (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 46(5):1133–1140

Zhang X, Shen L, Zhang L (2013) Life cycle assessment of the air emissions during building construction process: a case study in Hong Kong. Renew Sust Energy Rev 17:160–169

Zhang Z, Wu X, Yang X, Zhu Y (2006) BEPAS—a life cycle building environmental performance assessment model. Build Environ 41(5):669–675

Zygomalas I, Efthymiou E, Baniotopoulos C, Blok R (2012) A newly developed life cycle inventory (LCI) database for commonly used structural steel components. Struct Infrastruct Eng 8(12):1173–1181