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Where to focus? Developing a LCA impact category selection tool for manufacturers of building materials

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ABSTRACT

Life cycle assessment (LCA) has been widely applied to improve the environmental performance of the building sector. However, due to the complexity of LCA results including the multitude of impact categories, decision makers of the building materials manufacturing industry are grappling with allocating their limited resources to the most influential impact categories. The aim of this article, therefore, is to propose an impact category selection tool that enables performance improvement of building materials without sacrificing the validity of LCA results. The developed method selects common building materials, and defines foreground processes that can be influenced by manufacturers of building materials and background processes that can hardly be impacted using the US Input-Output database. Following the life cycle impact assessment (LCIA) analysis with the ReCiPe2016 Midpoint method, our results indicate that, among the 18 impact categories of the ReCiPe2016 Midpoint method, *Global Warming Potential*, *Ozone Formation and Human Health*, *Fine Particulate Matter Formation*, *Ozone Formation and Terrestrial Ecosystems*, *Terrestrial Acidification*, and *Terrestrial Ecotoxicity* should be considered the first priority group while *Ionizing Radiation*, *Freshwater Eutrophication*, *Marine Eutrophication*, *Freshwater Ecotoxicity*, *Water Consumption* should be placed in the last priority group. It further suggests that by shifting the limited available resources to the first priority group, decision makers can readily improve the environmental performance of building materials during the manufacturing process. The contribution of the proposed selection tool lies in that it can be adapted by decision makers to different geographical contexts, LCIA methods, and building materials to efficiently ameliorate the environmental performance of the building sector.

1. Introduction

Life cycle assessment (LCA) has been increasingly recognised as a systematic tool to evaluate built environment's environmental impacts. While it was said that the building sector relied on LCA for tackling construction-related social and environmental problems (Ingrao et al., 2018), there are persisting barriers that have restricted LCA from been widely adopted with confidence in the building sector. One of these is the time-consuming inventory process that requires a large amount of input data, making it difficult to complete a LCA study based on primary data (Hetherington et al., 2014; Ferrari et al., 2021). Another prominent barrier is that stakeholders in the building sector cannot easily use the LCA tool to improve their environmental performance due to the complexity of LCA results (Bonnet et al., 2014; World Business Council for Sustainable Development, 2016). In order to further promote LCA application in the building sector, Feng et al. (2022) have called for the reduction of the complexity and difficulty of the LCA methodology.

The large number of impact categories of common LCIA methods is one major reason for the complexity of LCA results (Lasvaux et al., 2016). For example, the CML-IA method has 10 impact categories, the ReCiPe 2016 Midpoint method has 18, and the TRACI 2.1 method has another 10 impact categories (PRé, 2022). This is also evident in the Product Environmental Footprint Guide that includes 14 impact categories (European Commission, 2012, p.22), and the EN 15804+A2 that contains 13 impact categories (CEN/ TC 350, 2019) and 13 energy, material, and waste indicators. This is exacerbated by the existence of various LCIA methods, such as CML2002, ECO-indicator 99 and EDIP 2003 (European Commission, 2010). As a result, building material

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manufacturers cannot easily identify the most critical categories. Faced with the already challenging initiative to inject the LCA concept into manufacturing, this increases manufacturers' reluctance to bear additional burden in terms of workloads and costs to promote sustainable materials. However, according to the World Green Building CEN/ TC 350 (2019, p.7), decarbonising the building sector has become "one of the most cost effective ways to mitigate the worst effects of climate breakdown''. Therefore, it is important that a more dynamic LCIA method that can identify the highlights of LCA results is developed to support manufactures in their decision makings.

Existing scholarships tended to streamline LCA without significantly affecting the overall results. This was often achieved through streamlining LCA: (1) at the life cycle inventory (LCI) phase; and (2) at the life cycle impact assessment (LCIA) phase (Arzoumanidis et al., 2014; Heidari et al., 2019). Among them, Malmqvist et al. (2011) recommended a simplified LCA (SLCA) method of buildings by simplifying inventory analysis and focusing on a few impact categories. Similarly, Karami et al. (2015) proposed a SLCA method by simplifying the data acquisition in the production phase and considering only the production and operational phases. Soust-Verdaguer et al. (2016) conducted a review on recent SLCA development and concluded that the simplification effort mainly focused on system boundary and results communication. Beemsterboer et al. (2020) reviewed LCA simplification strategies, categorised them and listed main concerns. In particular, they mentioned that the use of limited proxy indicators (one of the simplification techniques) as impact categories could risk information loss and could not reflect the real environmental impact. Considering different environmental impact categories with the lack of databases, Heidari et al. (2019) examined a SLCA method for building materials. However, their results were not comparable with full LCA results.

Clearly, extant SLCA studies are not able to find the best solution to reduce the complexity of LCA while maintain the accuracy of LCA results. For example, although the strand focused on the LCI phase simplified the LCA model by reducing the data collection efforts, they only considered the main elements and processes and thus jeopardised LCA's accuracy. For studies that targeted the LCIA phase, they reduced the number of impact categories to simplify the communication of the results. Failure to include all the environmental impacts created in the building sector, however can lose important environmental information (Arzoumanidis et al., 2014; Heidari et al., 2019). Hence, a new SLCA method that takes into account both LCA's convenient implementation and the completeness and accuracy of LCA results is urgently needed in the building sector.

Therefore, this study aims to develop an impact category selection method that can maintain the accuracy of LCA results while identifying the most important LCIA impact categories. Specifically, capitalising on different databases, such as the US Input-Output database (U.S. Bureau of Economic Analysis, 2023) and Ecoinvent database (Ecoinvent, 2023), it focuses on analysing the details of the LCIA phase and identifies the most important impact categories (i.e., the first priority group) of common building materials. Since the material manufacturing phase has the most diversity of flows and impacts on buildings' lifecycle, the ultimate goal of the proposed selection tool is to assist material manufacturers in the building sector in prioritising the most relevant impact categories, and diverting more resources to materials' manufacturing processes over which they have control. Now that the scene has been set, materials and methods adopted to develop the tool are explained next.

2. Materials and methods

There are a number of LCIA methods (e.g., CML2001, Eco-indicator 99, and ReCiPe) available for conducting a LCA (Dreyer et al., 2003; Acero et al., 2015). In this study, the ReCiPe 2016 Midpoint LCIA method (Huijbregts et al., 2017), which has 18 impact categories (shown in Table 1), was selected to analyse the interrelationships of the impact categories. This was because ReCiPe 2016: (1) contains the broadest set of midpoint impact categories; (2) enables impact categories to implement characterisation factors at an international scale; and (3) does not include potential impacts from future extractions in the impact assessment and assumes that they have been included in the inventory analysis, which are different from other approaches (e.g., Eco-indicator 99, Impact, 2002+) (ReCiPe, 2016). Due to its applicability to a specific country or continent, North America was chosen to identify the most important impact categories in its building sector. Commonly used building materials were defined based on five recent case studies of North American buildings. The materials of each building and the summarised building material list used in this study are shown in Table 2. At this juncture, it should be noted that the proposed selection tool can be performed in other regions following its detailed methods articulated below (see Fig. 1 below).

Table 1
The LCIA method and list of impact categories analysed in this study.

LCIA method	Impact Category	Abbreviation	Unit
ReCiPe 2016 Midpoint (H) v1.1	Global warming potential	GWP	kg CO_2 to air eq.
	Stratospheric ozone depletion	SOD	kg CFC-11 eq.
	Ionizing radiation	IR	kBq Cobalt-60 to air eq.
	Ozone formation, Human health	OFHH	kg NO_x eq.
	Fine particulate matter formation	FPMF	kg $PM_{2.5}$ to air eq.
	Ozone formation, Terrestrial ecosystems	OFTE	kg NO_x eq.
	Terrestrial acidification	TA	kg SO_2 to air eq.
	Freshwater eutrophication	FE	kg P to freshwater eq.
	Marine eutrophication	ME	kg N to marine eq.
	Terrestrial ecotoxicity	TET	kg 1,4-DCB to industrial soil eq.
	Freshwater ecotoxicity	FET	kg 1,4-DCB to freshwater eq.
	Marine ecotoxicity	MET	kg 1,4-DCB to marine water eq.
	Human carcinogenic toxicity	HCT	kg 1,4-DCB eq.
	Human non-carcinogenic toxicity	HNCT	kg 1,4-DCB eq.
	Land use	LU	$m^2 \times$ yr annual cropland eq.
	Mineral resource scarcity	MRS	kg Cu eq.
	Fossil resource scarcity	FRS	kg oil-eq.
	Water consumption	WC	m^3 water-eq. consumed

In order to identify the impact categories that should be prioritised in the building sector, the unit processes that contribute to each impact category should be analysed. The concepts of foreground (F) process and background (B) process were introduced to help classify the unit process. In this study, if the process is under the control of the decision-maker for which LCA is carried out, this process was defined as foreground process. By contrast, if the decision-maker's influence on the process is limited or indirect, it was defined as background process (Frischknecht, 1998; Hofstetter, 2000). In this case, when the majority of the processes that contribute to impact category A[1] were classified as foreground processes, impact category A should be highlighted since the decision-maker has direct influence on the majority of its contributors. Correspondingly, when the majority of the processes that contribute to impact category B were classified as background processes, impact category B were not considered in the top priority group. This was

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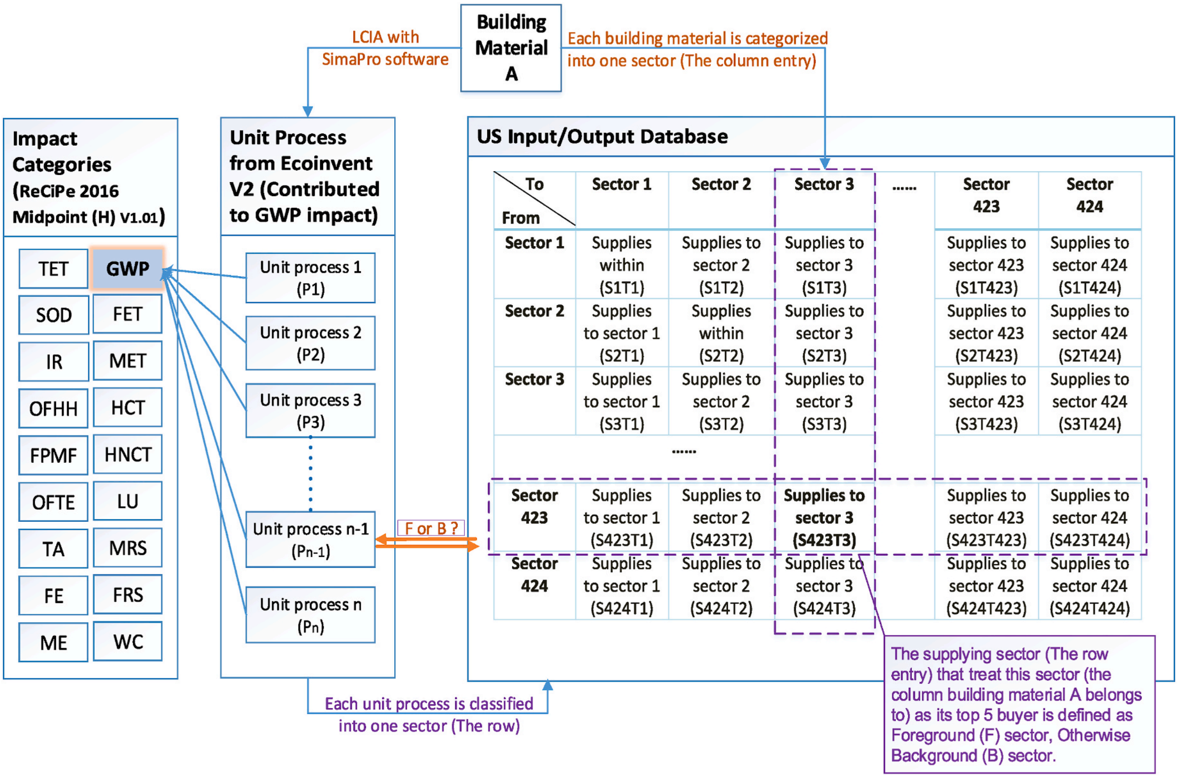
[1] A and B are code names used for the impact categories. They can be any specific impact category listed in Table 1.

Table 2
Commonly used building materials in North America.

Building example 1 (Feng et al., 2020)	Building example 2 (Reza et al., 2014)	Building example 3 (Meneghelli, 2018)	Building example 4 (Dixit et al., 2015)	Building example 5 (Shirazi and Ashuri, 2018)	Commonly used building materials summary
Gravel, Concrete slab, Concrete wall, Wood studs, Batt insulation, Gypsum board, Plastic film insulation, XPS rigid insulation, Aluminium window frame, Stucco, Plywood sheathing, Glazing, Wood door, Hardwood flooring, Wood joist, Wood strapping, Asphalt shingle, Roof membrane, Loose fill insulation	Concrete, Rebar, Gypsum board, Polyethylene film, Aluminium, Batt insulation, Galvanized sheet, Softwood lumber, Glazing, Modular brick, Mortar, PVC, Latex paint, Softwood plywood, Organic felt, Felt shingles, EPDM membrane	Reinforced steel, Aggregate, Concrete, Wire mesh, Glazing, Aluminium, Mineral wool insulation, Gypsum board, Particle board, Wood door	Concrete, Steel, Wood lumber, Plywood, Paints, Adhesive, PVC pipes, Poly foam insulation, Bricks, Glazing, Gypsum board, Mineral wool insulation, Aluminium, Copper, Carpet, Clay floor tiles,	Concrete, Wood studs, Alkyd solvent-based paint, Batt insulation, Cedar siding, Glazing, Wood door, Plywood, 6 mil polyethylene, Gypsum board, Brick, Wood joist flooring, Asphalt shingle	Concrete, Reinforcing steel, Gravel, Paint, Aluminium, Bricklaying mortar, Clay brick, Copper pipe, Glass, Galvanized steel pipe, Inner wood door, Poly foam insulation, PVC pipe, Softwood lumber, Softwood plywood, Gypsum board, Ceramic tile, Asphalt roof tile,



From \ To	Sector 1	Sector 2	Sector 3	......	Sector 423	Sector 424
Sector 1	Supplies within (S1T1)	Supplies to sector 2 (S1T2)	Supplies to sector 3 (S1T3)		Supplies to sector 423 (S1T423)	Supplies to sector 424 (S1T424)
Sector 2	Supplies to sector 1 (S2T1)	Supplies within (S2T2)	Supplies to sector 3 (S2T3)		Supplies to sector 423 (S2T423)	Supplies to sector 424 (S2T424)
Sector 3	Supplies to sector 1 (S3T1)	Supplies to sector 2 (S3T2)	Supplies to sector 3 (S3T3)		Supplies to sector 423 (S3T423)	Supplies to sector 424 (S3T424)
		......				
Sector 423	Supplies to sector 1 (S423T1)	Supplies to sector 2 (S423T2)	**Supplies to sector 3 (S423T3)**		Supplies to sector 423 (S423T423)	Supplies to sector 424 (S423T424)
Sector 424	Supplies to sector 1 (S424T1)	Supplies to sector 2 (S424T2)	Supplies to sector 3 (S424T3)		Supplies to sector 423 (S424T423)	Supplies to sector 424 (S424T424)

Fig. 1. The methodology flow.

because decision-makers often have limited impact on them to improve their environmental performance. For instance, concrete producers do not have a direct impact on coal mining processes. Therefore, coal mining would be a background process when studying concrete's environmental impacts. Paying attention to foreground processes is reasonable as Silva et al. (2020) have confirmed that they contribute to most impact results of construction products.

The Input-Output (IO) method was adapted in order to determine whether a process was foreground or background for a specific building material. The IO method describes the sell and purchase relationship between different economic sectors within an economy (World Input-Output Database, 2013). Specifically, due to the context of North America, the US IO database in SimaPro 8.5.2.0 was employed for the analysis. In the IO database matrix, the column entries typically represent the inputs one sector purchases from other sectors, while the row entries represent the outputs one sector sells to other sectors (Horowitz and Planting, 2009). The top values in Row A represent the top buyers from Sector A who can influence the decision-making process of Sector A. Therefore, if one process P_i (i indicates the number of processes) is categorised into Sector A and building material A belongs to a top buyer of Sector A, then the process P_i can be defined as a foreground process for building material A.

Based on the theory introduced above, the methodology, which defines the impact categories that should be highlighted for this study, is developed and illustrated in Fig. 1. This is further explained below.

1) Categorising building material A (this is a repetitive process and applies to all other materials in Table 2) into one sector among the column entries in the US IO database;
2) Ranking the supply sector of each row entry (from 1 to 424) in the US IO database and highlighting the supply sectors in which the building material A is the top five buyer. The highlighted sectors are defined as foreground sectors. In order to avoid the subjective definition on the boundary setup, a sensitivity analysis is conducted by changing the highlighted sectors from the top five buyer to top 10, 20, 30, and 50 buyers to recalculate the foreground and background sectors. Then the F/B distributions for each impact category are summarised and compared;
3) Conducting LCIA with the ReCiPe 2016 Midpoint (H) method and Ecoinvent database.
4) Sorting out all the Ecoinvent unit processes that contribute to each impact category (after 0.5% cut-off rule), and categorising each unit process into one sector among the row entries in the US IO database. The unit process that belongs to the highlighted sectors in step 2) is categorised as foreground process. The unit processes that happen in the material manufacturing factories, such as the combustion of fuels by machines/equipment, are also categorised as foreground processes; and
5) Separating and summarising the contributions between the foreground and background processes for each impact category. Highlight the impact categories that are dominated by foreground processes.

The building material - concrete was used as an example to demonstrate the methodology flow shown in Fig. 1. Firstly, we categorised 'concrete' into the sector 'ready-mix concrete manufacturing' in the US IO database. Secondly, we ranked the supply sectors based on the numbers in each row entry. Supported by the sensitivity analysis explained in Step 2), the sectors that treated 'ready-mix concrete manufacturing' as a top five buyer were: (1) 'ready-mix concrete manufacturing'; (2) 'cement manufacturing'; (3) 'sand, gravel, clay, and ceramic and refractory minerals mining and quarrying'; (4) 'stone mining and quarrying'; and (5) 'truck transportation''. Top five buyers were selected in this study as a demonstration. This can be extended to more buyers (or percentage of the total entries in a row). Therefore, the unit processes that belonged to any of these five sectors were defined as foreground processes. Thirdly, we conducted the LCIA for 'concrete' using the ReCiPe 2016 Midpoint (H) method and the Ecoinvent database. The contribution of unit processes for each impact category listed in Table 1 were generated. Fourthly, we categorised each unit process contributing to the impact results as a foreground or background process based on the rules shown in Step 4). Table 3 shows the contributing processes for the GWP impact category and the foreground and background categorisation for each process. Finally, we summarised the contributions in Table 3. In this case, as 89.6% of GWP contribution was from foreground processes and less than 10% of GWP contribution was from background processes, the GWP impact factor for 'concrete' was highlighted.

3. Results

By calculating the percentage of foreground unit processes with the five steps explained in Section 2, results of each impact category for the common building materials listed in Table 2 are synthesised in Table 4. The percentage in Table 4 represents the accumulated contributions of unit processes that were categorised as foreground processes at each impact category. The highlighted impact categories mean that their majority of contributions came from the foreground unit processes.

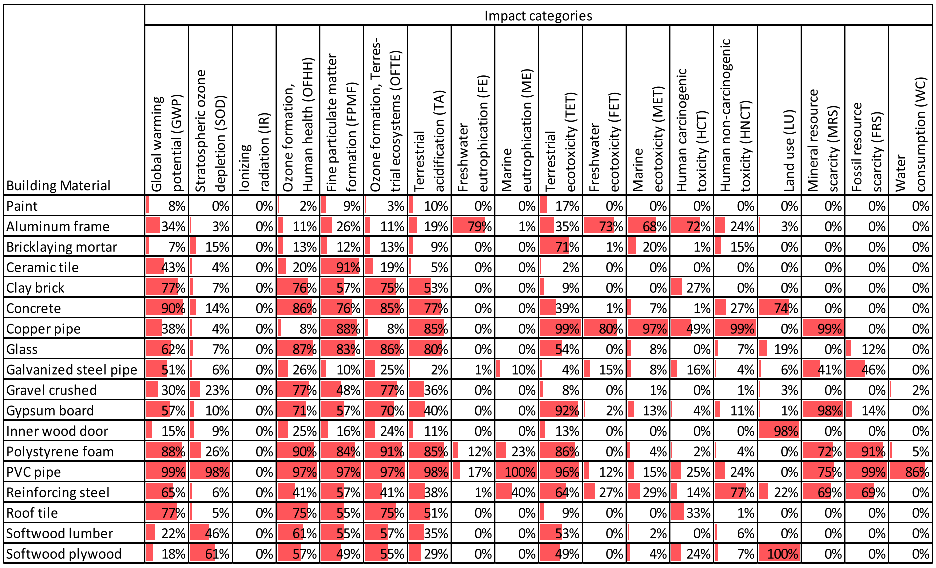
Table 3
Contribution processes for GWP impact category from LCIA of concrete.

No.	Ecoinvent unit process	Process classified into the IO database sector	Contribution Percentage	Foreground/ background classification
1	Clinker, at plant/ CH U	Cement manufacturing	86%	F
2	Diesel, burned in building machine/GLO U	Ready-mix concrete manufacturing	2.0%	F
3	Hard coal, at mine/WEU U	Coal mining	1.9%	B
4	Light fuel oil, burned in industrial furnace 1 MW, non-modulating/CH U	Ready-mix concrete manufacturing	1.0%	F
5	Lignite, burned in power plant/DE U	Electric power generation, transmission, and distribution	0.6%	B
6	Natural gas, sweet, burned in production flare/ MJ/GLO U	Oil and gas extraction	0.7%	B
7	Natural gas, vented/GLO U	Oil and gas extraction	0.8%	B
8	Operation, barge/ RER U	Water transportation	0.6%	B
9	Operation, lorry 20-28t, fleet average/CH U	Truck transportation	0.6%	F
10	Pig iron, at plant/ GLO U	Iron ore mining	0.5%	B
Total of all processes			100%	
Remaining processes (0.5% cut-off)			5.4%	

The results presented in Table 4 show that plastic materials, such as polystyrene insulation foam and PVC pipe, and metal materials, such as copper pipe and reinforcing steel, have the highest number of impact categories that were mainly contributed by foreground unit processes. The same pattern exists for concrete and gypsum board, which also have the majority of impact categories that were mainly contributed by foreground unit processes. In comparison, paint, bricklaying mortar, ceramic tile and inner wood door have the lowest number of impact categories that were mainly contributed by foreground unit processes. In addition, among the 18 impact categories, GWP, OFHH, FPMF, OFTE, TA, and TET are identified to be the highlighted impact categories for most of the building materials. In other words, these impact categories should be considered important in improving the LCA performance of the building sector. On the other hand, IR, FE, ME, FET and WC are not the highlighted impact categories for most of the building materials. Accordingly, these impact categories are not in the top priority group for decision makers to improve the LCA performance of the building sector. Notably, IR and WC almost have zero foreground process contribution to each of the 18 building materials. This is because the major unit process that contributed to an average of 90% of the IR impact category for each building material is 'tailings, uranium milling', which is the waste treatment process of nuclear power stations. The major unit process that contributed to an average of over 90% of the WC impact category for each building material is 'electricity, hydropower, at run-of-river power plant', which is the resource for hydropower generation. For both unit processes, decision makers (at the manufacturing stage) in the building sector cannot exert influence as the electricity generated by the nuclear power station or the hydropower station is used in a variety of industries other than the building sector. This is supported by the fact that the building construction sector was not ranked the top five buyers of the electricity generated by either nuclear power station or hydropower station. However, this is not to say that WC is not an important impact

Table 4

The percentage of the impact result caused by foreground processes for building materials (ReCiPe Midpoint (H) method).



	Impact categories																	
Building Material	Global warming potential (GWP)	Stratospheric ozone depletion (SOD)	Ionizing radiation (IR)	Ozone formation, Human health (OFHH)	Fine particulate matter formation (FPMF)	Ozone formation, Terres-trial ecosystems (OFTE)	Terrestrial acidification (TA)	Freshwater eutrophication (FE)	Marine eutrophication (ME)	Terrestrial ecotoxicity (TET)	Freshwater ecotoxicity (FET)	Marine ecotoxicity (MET)	Human carcinogenic toxicity (HCT)	Human non-carcinogenic toxicity (HNCT)	Land use (LU)	Mineral resource scarcity (MRS)	Fossil resource scarcity (FRS)	Water consumption (WC)
Paint	8%	0%	0%	2%	9%	3%	10%	0%	0%	17%	0%	0%	0%	0%	0%	0%	0%	0%
Aluminum frame	34%	3%	0%	11%	26%	11%	19%	79%	1%	35%	73%	68%	72%	24%	3%	0%	0%	0%
Bricklaying mortar	7%	15%	0%	13%	12%	13%	9%	0%	0%	71%	1%	20%	1%	15%	0%	0%	0%	0%
Ceramic tile	43%	4%	0%	20%	91%	19%	5%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%
Clay brick	77%	7%	0%	76%	57%	75%	53%	0%	0%	9%	0%	0%	27%	0%	0%	0%	0%	0%
Concrete	90%	14%	0%	86%	76%	85%	77%	0%	0%	39%	1%	7%	1%	27%	74%	0%	0%	0%
Copper pipe	38%	4%	0%	8%	88%	8%	85%	0%	0%	99%	80%	97%	49%	99%	0%	99%	0%	0%
Glass	62%	7%	0%	87%	83%	86%	80%	0%	0%	54%	0%	8%	0%	7%	19%	0%	12%	0%
Galvanized steel pipe	51%	6%	0%	26%	10%	25%	2%	1%	10%	4%	15%	8%	16%	4%	6%	41%	46%	0%
Gravel crushed	30%	23%	0%	77%	48%	77%	36%	0%	0%	8%	0%	1%	0%	1%	3%	0%	0%	2%
Gypsum board	57%	10%	0%	71%	57%	70%	40%	0%	0%	92%	2%	13%	4%	11%	1%	98%	14%	0%
Inner wood door	15%	9%	0%	25%	16%	24%	11%	0%	0%	13%	0%	0%	0%	0%	98%	0%	0%	0%
Polystyrene foam	88%	26%	0%	90%	84%	91%	85%	12%	23%	86%	0%	4%	2%	4%	0%	72%	91%	5%
PVC pipe	99%	98%	0%	97%	97%	97%	98%	17%	100%	96%	12%	15%	25%	24%	0%	75%	99%	86%
Reinforcing steel	65%	6%	0%	41%	57%	41%	38%	1%	40%	64%	27%	29%	14%	77%	22%	69%	69%	0%
Roof tile	77%	5%	0%	75%	55%	75%	51%	0%	0%	9%	0%	0%	33%	1%	0%	0%	0%	0%
Softwood lumber	22%	46%	0%	61%	55%	57%	35%	0%	0%	53%	0%	2%	0%	6%	0%	0%	0%	0%
Softwood plywood	18%	61%	0%	57%	49%	55%	29%	0%	0%	49%	0%	4%	24%	7%	100%	0%	0%	0%

category that decision makers should not focus on. Based on the results in Table 4, it purely demonstrates that the unit processes of 'tailings, uranium milling' and 'electricity, hydropower, at run-of-river power plant' may not be something that those decision makers have a control of. Tables A1-A3 in Appendix A present the most significant unit processes for each impact category of building materials. Table 5 summarises the contribution percentage by the top three unit processes for each building material.

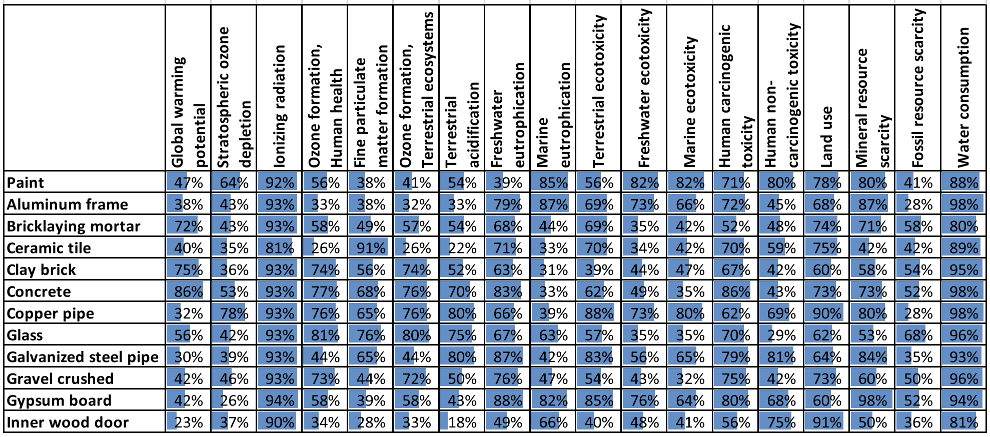
It can be seen from Table 5 that the top three unit processes contribute to more than 50% of the impacts on average for each impact category. As mentioned above, IR and WC receive the highest impact contribution from the top three unit processes. They are followed by FE, HCT, LU and MRS, which receive more than 70% of the impacts from the top three unit processes.

FE occurs due to the discharge of nutrients into soil or into freshwater bodies (Huijbregts et al., 2017). Therefore, the unit processes that contribute to FE impact can be related to waste disposal. In fact, Tables A1-A3 indicate that different waste disposal to residual material landfill or surface landfill is the most important unit process that contributes to around 50–90% of the impacts of FE except for the aluminium frame. However, the waste disposal process of different materials merely has any connection with the building materials since this is mainly the mining waste disposal listed in Ecoinvent database. This is evidenced in the IO database where the sector 'waste management and remediation services', that the waste disposal process belongs to, was not ranked as the top five suppliers for any building material listed in Table 2. Therefore, the waste disposal process is defined as background process, implying that FE should not be in the first priority group in LCIA to improve the sustainability of building materials. Comparing with the impacts to freshwater from mining waste, the impacts from construction waste are not in the same scale. Construction wastes are properly isolated, recycled or treated in the landfill to maintain minimum contact with freshwater, while the mining wastes are in a large quantity which include many hazardous components (Hu et al., 2020). This is the same case for HCT as different waste disposal to residual material landfill or surface landfill process is also a background process and the most important unit process.

In term of the LU impact factor, 'softwood/hardwood standing,

Table 5

Environmental impact contribution percentages due to the top three unit processes of each building material.



	Global warming potential	Stratospheric ozone depletion	Ionizing radiation	Ozone formation, Human health	Fine particulate matter formation	Ozone formation, Terrestrial ecosystems	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Land use	Mineral resource scarcity	Fossil resource scarcity	Water consumption
Paint	47%	64%	92%	56%	38%	41%	54%	39%	85%	56%	82%	82%	71%	80%	78%	80%	41%	88%
Aluminum frame	38%	43%	93%	33%	38%	32%	33%	79%	87%	69%	73%	66%	72%	45%	68%	87%	28%	98%
Bricklaying mortar	72%	43%	93%	58%	49%	57%	54%	68%	44%	69%	35%	42%	52%	48%	74%	71%	58%	80%
Ceramic tile	40%	35%	81%	26%	91%	26%	22%	71%	33%	70%	34%	42%	70%	59%	75%	42%	42%	89%
Clay brick	75%	36%	93%	74%	56%	74%	52%	63%	31%	39%	44%	47%	67%	42%	60%	58%	54%	95%
Concrete	86%	53%	93%	77%	68%	76%	70%	83%	33%	62%	49%	35%	86%	43%	73%	73%	52%	98%
Copper pipe	32%	78%	93%	76%	65%	76%	80%	66%	39%	88%	73%	80%	62%	69%	90%	80%	28%	98%
Glass	56%	42%	93%	81%	76%	80%	75%	67%	63%	57%	35%	35%	70%	29%	62%	53%	68%	96%
Galvanized steel pipe	30%	39%	93%	44%	65%	44%	80%	87%	42%	83%	56%	65%	79%	81%	64%	84%	35%	93%
Gravel crushed	42%	46%	93%	73%	44%	72%	50%	76%	47%	54%	43%	32%	75%	42%	73%	60%	50%	96%
Gypsum board	42%	26%	94%	58%	39%	58%	43%	88%	82%	85%	76%	64%	80%	68%	60%	98%	52%	94%
Inner wood door	23%	37%	90%	34%	28%	33%	18%	49%	66%	40%	48%	41%	56%	75%	91%	50%	36%	81%

under bark, in forest' is the most important unit process for most of the building materials, contributing to a range of 20–98% of LU impact with a mean value of 42%. This unit process is categorised into 'veneer and plywood manufacturing', which is defined as background process for most of the materials except for inner wood door and softwood plywood. This means that the LU impact factor may not be in the first priority group to improve the sustainability of building materials. For the MRS impact factor, 'Ferronickel, 25% Ni, at plant', 'molybdenum concentrate, main product', and 'Iron ore, 46% Fe, at mine' are the three most important unit factors for most of the building materials, which contribute to a range of 8–98% of the MRS impact category with a mean value of 51%. Specifically, 'Ferronickel, 25% Ni, at plant' is categorised into the 'copper, nickel, lead, and zinc mining' IO category, 'molybdenum concentrate, main product' is categorised into the 'gold, silver, and other metal ore mining' IO category, and 'Iron ore, 46% Fe, at mine' is categorised into the 'Iron ore mining' IO category. Therefore, the MRS impact factor should be considered as metallic materials such as copper and reinforced steel. For the other materials, these three unit processes are categorised as background process, and thus should not be the in the first priority group for improving the sustainability of building materials.

The cut-off rule in this LCIA study is 0.5% (Table 3), indicating that the contribution of unit processes that is lower than 0.5% are not included in Table 4. This cut-off processes turned out to have minimum impact on the results as over 90% of contributions were considered as an average in the LCIA for each impact category over the 18 materials. Within the IO database, the top 30 unit processes often contribute to over 90% of the impacts, and the rest of over 1900 unit processes engenders less than 10% of the impacts. Moreover, the values of impact categories for some materials are mainly from the top unit processes as shown in Table 5. Therefore, combing Tables 4 and 5, the 18 impact factors in the ReCiPe 2016 method can be divided into three levels of priority groups for decision makers in the building sector to improve the sustainability of building materials. That is, the first priority group encompasses GWP, OFHH, FPMF, OFTE, TA, and TET, the second priority group includes SOD, MET, HCT, HNCT, LU, MRS, and FRS, and the last priority group covers IR, FE, ME, FET, WC.

When interpreting the three priority groups for the impact categories, it should be reiterated that results shown in Tables 4 and 5 are based on the definition of background/foreground processes in the IO database, namely the supplying sector (the row entry) that treats the material sector (the building material belongs to) as its top five buyer is defined as a foreground process for that material. Additionally, a sensitivity analysis has been conducted to avoid the subjective boundary definition for foreground/background processes as well as the three priority group categorisation. The F/B percentage calculation was also conducted by defining the top 10, 20, 30, and 50 buyers as foreground sectors in the IO database, respectively. Since the first priority group already has a majority of materials contributed by foreground processes, a larger categorisation boundary of foreground processes in different scenarios would make the F/B results of the first priority group more obvious. Therefore, the 12 impact factors from the second and last priority group were monitored in the sensitivity analysis. Figure A1 in Appendix A depicts the changes on foreground percentages of each material in different F/B thresholds scenarios.

According to the sensitivity analysis (Figure A1 in Appendix A), the foreground percentage does not change on the second and last priority group when the foreground categorisation boundary changes from the top five sectors to the top 10 sectors except for the insulation material polystyrene foam. Next, when the foreground categorisation boundary changes from the top 10 sectors to the top 20 sectors, the foreground percentage on most of the building materials keeps the same except for roof tile, ceramic tile and clay brick materials. By contrast, when the foreground categorisation boundary exceeds 20 sectors, more than half of the building materials start to show increments on foreground percentage. Nevertheless, the accuracy of the proposed selection tool can be hindered if more than 20 sectors are considered as important suppliers of a building material. More importantly, this opposes the objective of this study to reduce the complexity of LCA results. As such, changes on foreground percentage emanated from setting more than 20 sectors as the foreground sector do not need to be considered while developing the proposed selection tool. Therefore, the priority group categorisation (the three groups as listed above) for the impact categories is reliable and the foreground categorisation boundary in the IO database does not have a large impact on it.

4. Discussion

With the proposed selection method, Section 3 has identified the importance of LCIA impact categories of the ReCiPe 2016 Midpoint method to be three priority groups. Reliability of this categorisation was also ensured through a sensitivity analysis. Having in place the proposed selection tool would enable decision makers (at the manufacturing stage) to exploit their limited resources to further improve the environmental performance of the building sector (Fig. 2). As illustrated in Fig. 2, emphases are placed on foreground processes because decision makers can exert direct influence on them (Section 2), and they have significance impact on impact categories of building materials (Silva al., 2020). We now discuss the proposed selection tool in terms of the midpoint and endpoint impact categories in the ReCiPe method, its relationship with existing studies, and the advantages over the building rating systems. It should be noted, however, that our proposed method can be applied beyond the building sector. The results (e.g., different priority groups of impact categories) may be different, but the way our method is used remains the same. This is because each sector has its own features and we selected the building sector as a typical case.

The endpoint categories include damage to human health, damage to ecosystem quality, and damage to resource availability (Huijbregts et al., 2017). In this study, the midpoint categories that were identified as the first priority group covered two of the three end-point categories (i.e., damage to human health and damage to ecosystems). Specifically, GWP, OFHH, and FPMF are related to damage to human health in the endpoint category, and OFTE, TA, and TET belong to damage to ecosystems in the endpoint category. This demonstrates that the proposed selection tool is not only able to account for the midpoint but also the majority of endpoint. Even for 'damage to resource availability', it was evaluated via the two midpoint categories - MRS and FRS. However, based on Tables A1-A3, the major unit processes for MRS are mostly mineral raw materials such as bauxite, ferronickel, and iron ore. As these materials are also commonly used raw materials in a lot of other economic sectors (e.g., the petroleum industry) than the building sector, decision makers for manufacturing building materials often do not have enough influence on such material sectors and the associated unit processes.

Similarly, the major unit processes for FRS are mostly the original sources for energy, such as crude oil, hard coal, natural gas, and lignite, which are basic needs for all kinds of economic sectors that demand energy consumption. As the building material manufacturing sector is not a significant buyer of fossil resources, the possibility that these fossil resource sectors accept the influence from the building material sector greatly decreases. Therefore, it is reasonable not to consider the MRS and FRS impact category (representing the damage to resource availability in the endpoint) as the first priority group from an economic perspective (i.e., limited resources). The report of International Energy Agency (2021) also illustrated that the buildings construction industry (as part of the overall buildings and construction industry) shared 6% of global energy in 2020. Although a single manufacturer cannot significantly influence the energy sector, there are strides to be made to reduce the energy resource depletion in building and construction given its 36% share of global final energy in total.

There are a lot of studies that have been conducted to reduce the complexity of LCA results in addition to the selection tool proposed in

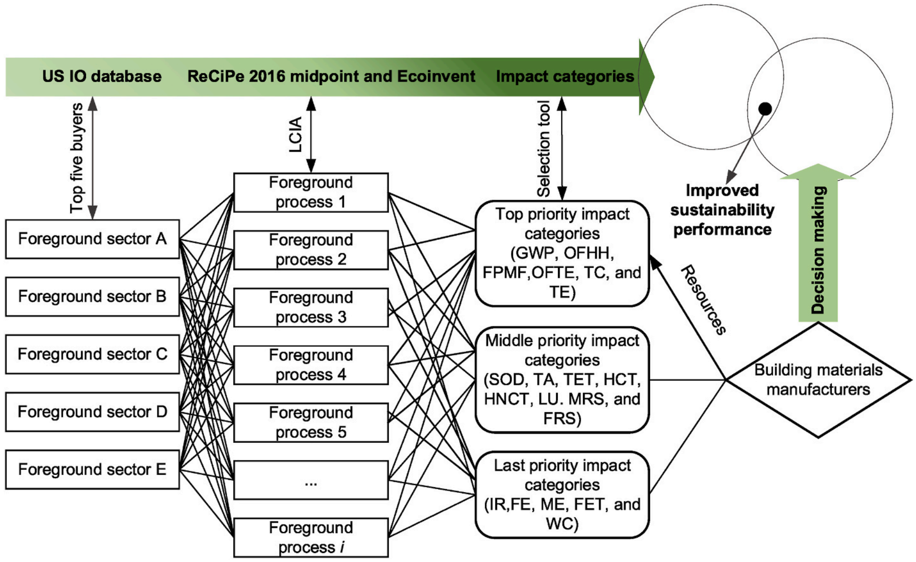


Fig. 2. The LCA impact category selection tool for building materials manufacturers.

this study (Lasvaux et al., 2016; Pascual-González et al., 2015). However, rarely is the case that a simplified LCA method focuses on the economic influence perspective since resources available to decision makers are limited. Combining the economic consideration with LCA is important, because Meglin et al. (2022) demonstrate that the construction industry's transition towards sustainability must jointly coordinate these two aspects. Accordingly, this proposed impact category selection tool serves the purpose of identifying the most important processes to reduce the environmental impacts of materials manufacturing in the building sector from an economic perspective. Compared with the existing literature where LCA application coupled with simplified LCIA impact categories is fashionable but the simplification on LCA sometimes compromises the accuracy of final LCA results (Arzoumanidis et al., 2017; Kellenberger and Althaus, 2009), our proposed selection tool does not require this sacrifice as all LCA processes, from goal and scope definition to life cycle impact assessment, remain the same. Furthermore, the proposed selection tool highlights the most important impact categories that should be analysed based on their economic impacts on the unit processes, which can help reduce the LCA development work and further optimise the LCA outputs.

The ReCiPe 2016 Midpoint method has been adopted in this study to develop the selection tool. With the popularity of LCA method to improve the sustainability of building sector, there are quite a few LCIA methods available in the industry with different impact categories. For instance, such building rating systems as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) all have whole building LCA credits with different impact categories considered. As shown in Table A4, all three rating systems (i.e., LEED, BREEAM, and DGNB) include GWP, SOD, acidification, eutrophication, and tropospheric ozone formation. Table A4 also presents the impact categories that are considered by Environmental Product Declaration (EPD), which is the most popular environmental assessment system at a material level (Rangelov et al., 2021). Despite the fact that lots of reports have been generated for different kinds of building types and materials in the industry owing to all these LCA methods, they do not really provide any practical solution to further reduce the environmental impacts of buildings or materials as the rating systems often only provide a ranking/point for buildings (Doan et al., 2017). Without a background knowledge of LCA, owners of the building materials manufacturing business could barely understand the meaning of LCA results that include various impact categories. As the awareness of practically reducing the environmental impacts and improve material sustainability from the business owner's perspective increases, the impact categories selection tool developed in this study is at the right direction to help the building material manufacturing industry to select the impact categories that should be considered as a first priority based on the economic influence of this industry.

4.1. Future works

There are limitations of this study that should be cautiously taken for interpretations. Five buildings were selected as the foundation to identify the common building materials. This was because they represented the most recent and typical buildings in North America. However, it should be noted that differences exist between types of buildings (e.g., skyscrapers in cite centres and family houses in the countryside). For example, Foster (2020) studied strategies to reduce environmental impacts of cultural heritage buildings. Further research can be conducted to compare and synthesise the findings. In addition, while this study has identified three priority groups as a reference for decision makers, a follow-up investigation can examine the priority/weighting of impact categories within a specific group (e.g., the first priority group). This is to ensure manufacturers of building materials can concentrate closer on certain impact category(ies) if they think the number of impact categories are still overwhelming.

Correspondingly, other limitations of this study may also open an avenue for future works. The first direction links to the application of the proposed selection tool to other countries/continents with their associated building material list. In this study, the US IO database was chosen to develop the selection tool, and the building materials were selected based on the most commonly-used materials in North America. While the IO analysis has become one of the best methods to study the interconnections between unit processes and material manufacturing, and further define foreground and background processes (Igos et al., 2015), the US IO database was built up by Swiss life cycle inventories, which could create some uncertainties in representing the actual situation in the US as every country has its unique economic system, and the commonly-used materials there are different. Therefore, future works can utilise the World Input-Output Database (WIOD) that has a coverage of 43 countries and 56 economic sectors. An existing application of the WIOD can be seen in Lu (2017).

The second direction links to the identification and prioritisation of impact categories in other databases such as the Gabi and USLCI databases by using the proposed selection tool. In this study, the LCIA method - ReCiPe 2016 Midpoint was selected to conduct the analysis on impact categories. The aim of this study was to propose a new selection method to optimise the LCA results and help building material manufacturers to focus on the most noticeable impact categories in term of economic behaviours. Therefore, the proposed method is adaptable to any other LCIA methods, such as CML 2001, TRACI 2.1, or Ecoindicator 99. Although the database chosen in this study is not vital, the aforementioned direction can be researched to conduct a comparative study with other databases.

5. Conclusions

Coupling with the development of LCA methodology in the building sector is the complexity of LCA results that have concerned LCA practitioners. Addressing this issue, research has been conducted in the last decades in an attempt to simplify different parts of the LCA. However, extant methods are usually plagued by reduced reliability of the LCA results. In order to assist the building material manufacturers in focusing their limited resources on the most important parts of the LCA results, this study proposed a LCIA impact category selection tool from the economic influence perspective to improve the overall sustainability of building materials.

The most commonly-used building materials in North America were chosen to conduct the LCA. The ReCiPe 2016 Midpoint method was used to conduct the LCIA and generate all the unit process contributions to each impact category. In addition, the US IO database was chosen to link the unit process with each economic sector, and define the foreground and background processes. The results indicated that the 18 impact categories from the ReCiPe can be classified into three priority groups. The first priority group covered GWP, OFHH, FPMF, OFTE, TA, and TET, the second priority group included SOD, MET, HCT, HNCT, LU, MRS, and FRS, and the last priority group contained IR, FE, ME, FET, WC (Fig. 2). The LCIA contribution results also showed that around 50%–70% of the impacts were contributed by the top three unit processes. This was further confirmed by the sensitivity analysis, which illustrated that the definition boundary for foreground and background processes only had minor influence on the priority group categorisation. Although North America was demonstrated as an example, the proposed impact category selection tool can be expanded to other countries with different LCIA methods, building material lists, and LCA databases provided that they have I/O tables. Thus, the contribution of this study is mainly an impact category selection tool developed from an economic perspective. Such a tool can be readily adapted by decision makers of the building material manufacturing industry to efficiently improve the overall environmental performance of the building sector.

CRediT authorship contribution statement

Haibo Feng: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Jianfeng Zhao:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Alexander Hollberg:** Writing – review & editing. **Guillaume Habert:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136936.

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