



Strategic Decision Making in Construction Supply Chains: A Comparison of Reverse Logistics Strategies

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Most of the construction materials still go to landfill after structures are demolished. This causes issues in human health, ecosystem preservation, and excessive resource consumption compared to RL options. Hence, recovering material value through reverse logistics (RL) is important to lessen the environmental and social burden. Embodying RL practices into strategic level decisions derives long-term and sustainable advantages. Although the most common RL option in construction seems to be recycling, it requires an additional energy and material intensive process. Therefore, recycling should be the last preference among other RL options. The hypothesis of this study is that alternative RL strategies provide more environmental benefits than recycling, the most common RL method, and traditional landfilling. The hypothesis was tested through assessment of the environmental impact of RL options in the construction sector. A life cycle assessment (LCA) with ReCipe2016 Midpoint and Endpoint assessment method was conducted for a bridge construction supply chain. Different end-of-life scenarios such as reuse, remanufacture, recycle, and landfill scenarios were assessed using SimaPro software. This paper addresses a key knowledge gap on the environmental impact of reverse logistics strategies from a construction supply chain perspective. The research results reveal that “reuse” strategy has the least environmental impact, remanufacturing has a lesser impact on the environment than other options, recycling has the second highest environmental impact, with landfill assessed as the least environmentally friendly end-of-life option. Consequently, this paper emphasizes the importance of informed strategic supply chain decisions for reverse logistics to obtain the best outcome from environmentally friendly practices. Since there is no relevant previous research conducted to examine the environmental impact of different reverse logistics options from a construction supply chain perspective, the findings of this study provide crucial input in RL decision making and can extend to contributing to practice. Industry stakeholders, especially the government agencies and regulatory bodies,

should encourage practitioners to adopt the most effective RL approaches, including reuse and remanufacturing, rather than focusing only on material recycling. The motivation of supportive designs for more environmentally friendly RL options from the researchers, designers, architects, and planners are required in this process.

Keywords: bridge construction, construction industry, construction supply chain, environmental impact, life cycle assessments

INTRODUCTION

Making strategic decisions at the supply chain and organizational level is vital for obtaining a competitive advantage in the market arena. Strategic decision-making on sustainable practices is also important for gaining long-term positive impacts on all sustainable dimensions (Neugebauer et al., 2016; Malviya et al., 2018). Since most of the business activities have severe impacts on the natural environment and contribute to climate change, ozone depletion, water and air pollution, business entities are stimulated to follow healthy business practices in every possible way. Material production, processing, transportation, manufacturing, warehousing, distribution, and end-of-product life activities can create environmental issues (Ioppolo et al., 2019). As a response to such environmental issues, rules and regulations are imposed by authorities on business entities aiming to protect and secure the environment now and for the future (Kylili and Fokaides, 2017; Lin et al., 2020). The imposition of rules has perhaps become one of the drivers of the increased public awareness of environmental degradation of business activities and companies' uptake of corporate social responsibility in protecting the natural environment from supply chain activities. Sarkis et al. (2011) emphasize that societal and regulatory pressures are forcing business entities to adopt environment-friendly practices in their business activities.

The execution of sustainable procedures in any industry primarily depends on its supply chain networks (Lin et al., 2020). Construction industry has a significant negative impact on the environment from the entire construction process (Sertyesilisik, 2016). Thus, as an industry that consumes a vast quantity of materials that are energy-intensive, environmentally friendly practices are more significant to the construction industry than to some others. For example, this sector consumes around 60% of raw materials taken from the earth and 40% of energy production worldwide (Zabalza Bribián et al., 2011; Durdyev et al., 2018). Due to the unsustainable sourcing of energy used in material processing and the amount of these materials used in the construction process (Navarro et al., 2018), the environmental impact of construction operations is widespread. Excess CO₂ emissions, solid waste generation, natural resource depletion, higher water usage and contamination, and toxicity are some of the examples of these impacts (Durdyev et al., 2018).

Of particular interest are the manufacturing processes of the most commonly used construction materials: concrete and steel. Both are energy-intensive and require large amounts of materials to be extracted and processed (Zabalza Bribián et al., 2011); thus, their impact is argued to extend to global climate change, fossil fuel depletion, ozone depletion, air pollution, smog,

acidification, eutrophication, deforestation, desertification, soil erosion, habitat alteration, loss of bio-diversity, water resource depletion, ecological toxicity, and human health damage (Calkins, 2009). Globally, construction industry contributes to the depletion of natural resources (40%), greenhouse gas emission (18%), and waste (25%) (Teh et al., 2018), and consumes 40% of total energy (Dixit et al., 2010). Every phase of the construction life cycle, including the extraction and production of materials, construction, operation, and demolition, is energy- and CO₂-intensive (Ioppolo et al., 2019). For example, concrete consumption alone is estimated to contribute to about 8.6% of the total anthropogenic CO₂ produced globally (Miller et al., 2016). The construction industry is further identified as the biggest producer of non-toxic waste across the globe (Marzouk and Azab, 2014). For example, it generates over 500 million tons of waste per year in the European Union (Mália et al., 2013). In Australia, ~20 million tons of waste were produced nationally in 2016 (Australian Bureau of Statistics, 2019). Waste that is dumped into natural ecosystems can contaminate water, causes erosion, and creates hazards (Esin and Cosgun, 2007) and therefore, some governments adopt policies for the disposal of waste through landfilling to manage the construction and demolition (C&D) waste. For example, Canada utilizes 35% of land space as landfill areas for construction waste (Kofoworola and Gheewala, 2009). Throughout the world, the construction industry generates around 35% of landfill waste (Ajayi and Oyedele, 2017). In the UK, more than 50% of the landfill waste is construction waste (Kofoworola and Gheewala, 2009). Forty per cent of C&D waste is landfilled in Australia (Li and Du, 2015). Landfilling is costly; for example, the Hong Kong government spends HK\$ 200 million per year on waste disposal and uses landfill space at the rate of about 3,500 m³ per day (Poon et al., 2001). According to the Department of the Environment, Water, Heritage and the Arts in Australia (2009), the total cost of landfill ranges between \$42 and \$102 per ton, and it is between \$41 and \$101 per ton in urban and rural areas, respectively, based on management controls and the climate. Although landfilling is the most common way of disposing of waste, it leads to severe environmental pollution if it is not managed properly.

Despite the negative impacts, the construction industry is a significant component of any economy, as it contributes to economic growth and human well-being (Giang and Sui Pheng, 2011) through infrastructure investment in highways, power plants, railways, pipelines, dams, and residential and non-residential buildings, which are crucial for any nation. Therefore, effective approaches are mandatory to develop sustainable product life cycles that can drastically reduce environmental

impact, resource utilization, and generation of waste, while improving living conditions and company turnover (Fukushige et al., 2012). Preserving non-renewable resources for future generations has become a necessity as today's population growth, economy, and the increase in living standards accentuates the scarcities of available resources (Asif et al., 2012). A precise remedy for addressing this problem is to extend the life of used materials as much as possible to reduce the consumption of new resources and to avoid generating unnecessary waste.

Reverse logistics (RL) is the facilitator by which the products are reused, repaired, refurbished, remanufactured, and recycled (Fleischmann et al., 1997; Lau and Wang, 2009; Khor and Udin, 2013) and can be well-defined as "the process of planning, implementing, and controlling the flow of raw materials, inventories, finished products, and information, from the point of consumption or disposal of the goods to the point of origin, to recover remaining value or provide appropriate disposal" (Sellitto, 2018, p. 924). RL extends the life of products further, adds value to them, and is adopted as a strategy for curbing the environmental impact of business activities. It is a well-established concept in the manufacturing sector and due to its success, it has been adopted by other industries as well.

Recycling is the most common end-of-life RL strategy in managing construction-related waste compared to other options discussed in the construction industry-related literature (Pushpamali et al., 2019). However, it is imperative to comparatively analyze the environmental impact of different end-of-life strategies, such as reusing, repairing, refurbishing, remanufacturing, recycling, and landfilling, prior to making any strategic decision on RL in the construction industry. Products can be directly reused if they are in good condition, but products must be repaired to improve the working condition by replacing faulty parts if necessary. Products can be disassembled into modules, inspected, and replaced if necessary, then reassembled and upgraded to a different quality level by refurbishing. In remanufacturing, products are totally disassembled and required parts are replaced to improve the quality of the product to be similar to a new product. Cannibalization involves products being disassembled selectively and inspected; then the reusable parts are used in repairing, remanufacturing, and refurbishing other products. In recycling, products and components are disassembled into parts and processed as materials which can be used in new production (Schultmann and Sunke, 2007; Sobotka and Czaja, 2015). For recycling, it further demands energy and virgin materials (Chileshe et al., 2018). Therefore, there is no doubt that strategic decisions for RL should be made by assessing the entire life cycle of a project to examine its long-term effect at both upstream and downstream levels. As discussed by Fukushige et al. (2012), life cycle strategies must be planned in the early stages of the product design, where the product is designed to achieve these strategies.

Life cycle assessment (LCA) is a widely used tool that quantifies the environmental impact of products for their entire life cycle (Lee and Inaba, 2004). LCA is a comprehensive method extensively used in industries for estimating the environmental effect from the start (cradle) to the end (grave) of the life cycle of a product (Lee and Inaba, 2004; Pang et al., 2015). This

claim is supported on examining the objectives of conducting an LCA. As argued by Klopffer (1997), "the environmental burdens associated with a product or a service have to be assessed, back to the raw materials and down to waste removal" (p. 223). LCA is a feasible method for this intent. The robustness of this method is further emphasized by the International Organization for Standardization (ISO), which endorses the concept and promotes LCA for standardizing activities, specially, ISO 14040/44 (Xue and Xu, 2017).

It is important for the construction industry to consider environmentally friendly practices from a supply chain perspective. Although recycling of used materials seems to be the most popular RL strategy in this sector, there is an identified industry need to compare the environmental impact of different RL strategies to inform strategic decision making. Despite this, such analysis is still lacking in the literature. Thus, the purpose of this research is to quantify and compare the environmental performance of different RL strategies for construction industry using LCA. The study hypothesizes that alternative RL strategies provide greater environmental benefits than the most common RL method of recycling and traditional landfilling. A bridge construction supply chain case was developed to demonstrate the environmental impact of RL strategies across different end-of-life scenarios. ISO 14040:2006 guidelines were followed for the LCA process. LCA has been used successfully in construction industry-related research to assess the environmental impact of construction activities. For example, Fifer Bizjak and Lenart (2018) conducted an LCA to compare the environmental impact of different types of bridge construction with a focus on the overall environmental impact of conventional reinforced concrete bridge construction and of geosynthetic reinforced soil (GRS) bridge construction. The authors emphasized that the LCA results can be used as the basis for the preparation of environmental product declarations and guides as well as to identify significant points that required improvements to achieve effective environmental performance. Penadés-Plà et al. (2018) also used LCA to obtain environmental information related to a pre-stressed, pre-cast bridge and the authors relied on LCA in assessing the environmental effect of structures. Similarly, Hossain et al. (2016) conducted an LCA to estimate and examine the environmental impact of aggregates made from C&D waste along with natural aggregates, and the authors emphasized the importance of LCA in increasing environmental awareness in the industry. Pang et al. (2015) adopted LCA to examine the environmental impact of highway bridges of different strengths as previous studies have been conducted based only on economic costs. LCA was adopted to assess the impact of highway bridge on ecosystem quality, human health, resources, and energy for structures of different strengths. Hammervold et al. (2013) conducted an LCA for three types of bridges (e.g., steel box girder, concrete box girder and wooden arch) and believed environmental assessment to be significant for environmental design decision-making. Although the articles mentioned are limited in number, their currency and relevance to our research support the notion that LCA is a viable method to use for environmental analysis in construction industry-related activities.

MATERIALS AND METHODS

Life Cycle Assessment of a Bridge Construction Supply Chain

A case study of a bridge construction supply chain was developed for the Life Cycle Assessment (LCA) in Queensland, Australia. Bridge construction was selected for the environmental analysis as a bridge is a significant structure in the construction sector, enabling and facilitating transport of people from one place to another (Penadés-Plà et al., 2018). Further, it is a relatively simple structure, which consists primarily of concrete and steel. The ISO 14040:2006 guidelines were followed for the research. The LCA process should consist of four phases: goal and scope, inventory analysis, impact assessment and life cycle interpretation [International Organization for Standardization (ISO), 2006]. Since the study is built on a comparative analysis of different reverse logistics strategies, an attributional approach was adopted to conduct the research (Aberilla et al., 2020). The SimaPro software, developed by PRe-Consultants, was used for the assessments of this study as it is recognized as a powerful and flexible tool that can be applied to a wider range of contexts and its databank of processes can be modified (Colangelo et al., 2018). The sections below describe the phases of the LCA process further; however, the interpretation phase will be discussed in a separate section.

Goal and Scope of the Analysis

The goal of the life cycle assessment (LCA) was to compare the different types of potential end-of-life scenarios for the selected concrete bridge and assess the environmental impact of different RL strategies that can potentially mitigate the impact of construction operations. Only the contractor, the material supplier, and the material producer were considered as the supply chain stakeholders in this hypothetical bridge case. However, the structure of the bridge is real, with dimensions of 39.55 m (length) and 10.55 m (width) over the Brisbane River. The bridge dimensions were collected from a local contractor. Only direct reuse, remanufacture, recycling, and landfilling were considered as end-of-life scenarios. Repair and reuse were disregarded in this case study because a bridge, as an infrastructure asset, is not discarded due to minor issues.

Although the life cycle of the bridge can be divided into four phases, only three phases were considered for the study: the manufacturing of materials, construction, and end-of-life. The use phase was ignored, assuming end-of-life treatments do not affect the use phase of the bridge. The system boundary of the analysis is illustrated in **Figure 1**. Since the concrete quantities of different components of the bridge were considered in the study, the functional unit is considered as 1 m³ of concrete. Concrete was considered as the material required for the bridge construction. Cement—the one of the significant constituents of concrete—is largely used in the construction industry and is highly energy-intensive in its production and contributes substantially to environmental influence throughout its life cycle (Colangelo et al., 2018) The additional environmental impact of reinforcing steel that is used in reinforced concrete in bridge components has little effect on the life cycle assessment results

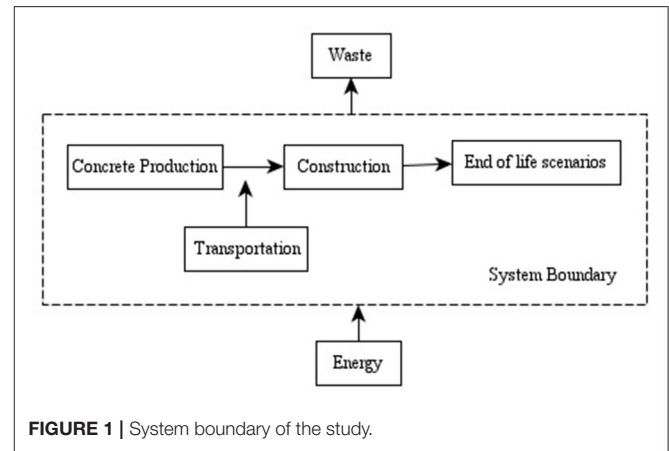


FIGURE 1 | System boundary of the study.

(Guggemos and Horvath, 2005). Steel can be recycled unlimited times; however, it is a different scenario to concrete together. Thus, the viability of this analysis is still substantial.

Inventory Data and Life Cycle Impact Assessment

Data for the study from raw materials processing and production (concrete), transportation, and construction to end-of life scenarios was adopted from Ecoinvent databases along with the Australian life cycle database. Construction operation related data was identified in the literature, and other relevant data was selected from the databases.

Impacts derived from life cycle activities are evaluated using standard methodologies (Navarro et al., 2018). The ReCiPe 2016 method was used for the impact assessment, as it consists of the full environmental profile with 18 impact categories at the midpoint and enables the normalization of three main damage categories with the endpoint category (Penadés-Plà et al., 2018). ReCiPe presents a modern approach to turning life cycle inventories into selected life cycle impact categories at midpoint and endpoint levels (Huijbregts et al., 2017).

The ReCiPe 2016 (Global-Hierarchist version) default midpoint method was considered in the analysis. Midpoint impact categories include particulate matter, ozone formation—human health, ionizing radiation, stratospheric ozone depletion, human toxicity (cancer), human non-toxicity (non-cancer), global warming, water consumption, freshwater ecotoxicity, freshwater eutrophication, ozone formation—terrestrial ecosystems, terrestrial ecotoxicity, terrestrial acidification, land use, marine ecotoxicity, marine eutrophication, mineral resources, fossil resources. Ionizing radiation and stratospheric ozone depletion. The damage pathway of impact categories is presented below.

Particulate matter and ozone formation (human health) lead to increases in respiratory diseases. Ionizing radiation, stratospheric ozone depletion, and human toxicity (cancer) cause various types of cancer. Ionizing radiation, stratospheric ozone depletion, human non-toxicity (non-cancer), and global warming increase other type of diseases. Global warming and

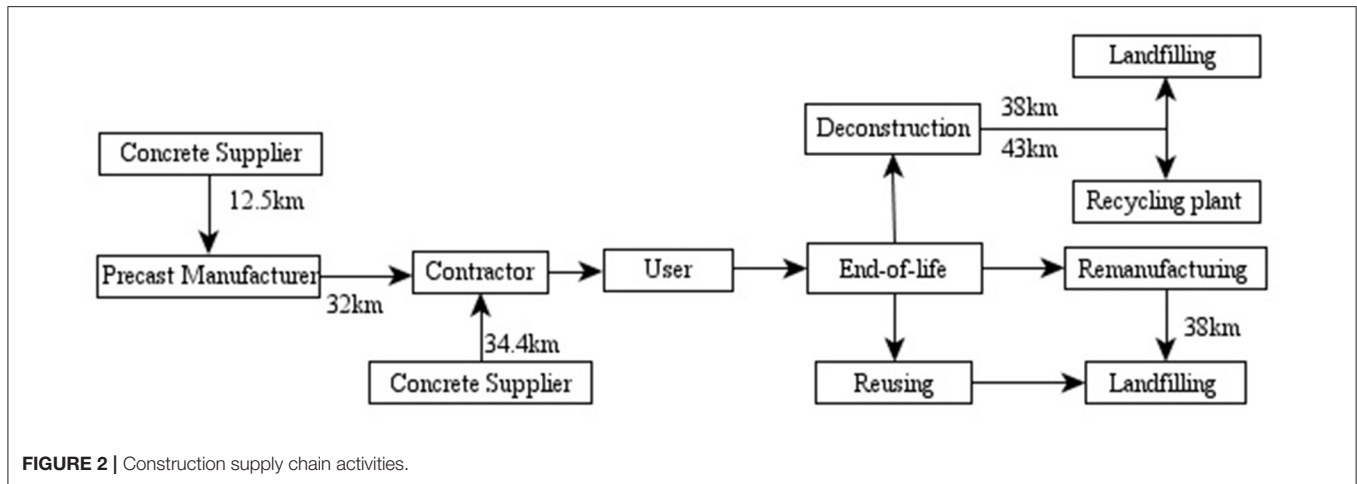


FIGURE 2 | Construction supply chain activities.

TABLE 1 | Bridge components and quantities.

Bridge components	Tons
Pier headstock	71.78
Abutment headstock	67.25
Piles	772.58
Deck	372.07
Kerb unit	83.38

water consumption lead to malnutrition. Global warming, water consumption, freshwater ecotoxicity and freshwater eutrophication cause damage to species in freshwater. Global warming, water consumption, ozone formation—terrestrial ecosystems, terrestrial ecotoxicity, terrestrial acidification and land use, damage terrestrial species. Marine ecotoxicity and marine eutrophication are causes of marine species damage. Mineral resources increase the extraction cost, while fossil resources incur energy cost.

Endpoint categories are detrimental to human health, ecosystems, and resource availability. As discussed in the above section, the increase of respiratory disease, various types of cancer, other diseases, and malnutrition are causes for damaging human health. Harming freshwater, terrestrial, and marine species cause damage to the ecosystem. Increased extraction and energy costs lead to damage resource availability [National Institute for Public Health and the Environment (NIPHE), 2017].

Case Study

Only the concrete supplier, a pre-cast components manufacturer, and a contractor were assumed as the stakeholders of the bridge construction supply chain and the contractor was considered to be the focal company of the supply chain (Figure 2). Only manufacturing, construction, and end-of-life were considered as phases of the life cycle and the use and maintenance phase was excluded assuming this phase does not vary between any end-of-life scenarios. Several assumptions were made in the case development for simplifying the case. The bridge was assumed to be developed at the location of 27.44463°S, 152.67108°E with the dimensions of 39.55 m (length) and 10.55 m (width) over

the Brisbane River in Australia. Pre-cast bridge components, such as piles, decks, and kerb units, were considered transported from the pre-cast part manufacturer, and abutment and pier headstocks were considered to be cast in place with the materials transported from suppliers (the quantities of bridge components [tons] are provided in Table 1). It was further assumed that the concrete required for pre-casting was provided by the same suppliers to the manufacturer of the pre-cast components. The locations of the supply chain activities are shown in Figure 3 below. The actual material requirements were considered for the calculations of concrete quantity for the bridge components, based on an actual bill of quantities provided by a contractor. Details of the bridge’s life cycle with assumptions made are further explained below.

The Life Cycle of the Bridge

The life cycle of the bridge consists of four phases: material production, construction, operation, and end-of-life; however, it was assumed that the operation aspect is not affected by RL decisions. Material production phase includes the production process of the materials required for the bridge. Concrete required for the pre-cast components is transported to the pre-cast plant, while materials necessary for the cast in place are transported to the construction site. The concrete supplier is located 34.4 km from the site, and the pre-cast plant is located 32 km from the site, while the concrete supplier is located 12.5 km from the pre-cast plant.

Construction phase consists only of the transportation of materials and equipment required for the building of the bridge. It is assumed that machinery consumes 123.42 MJ of energy and emits 32.24 kg of CO₂ per m³ of concrete, as stated by Penadés-Plà et al. (2018). The transportation and construction process is considered only for selected components of the bridge.

End-of-life phase consists of processes after the end-use of the bridge. The bridge’s useful lifetime is assumed to be 100 years (Lounis and Daigle, 2007), but it is used only for 50 years. For research purposes, four end-of-life scenarios after 50 years of the bridge life were developed:

- (1) The bridge is used for another 50 years after it is used for 50 years (Reuse).

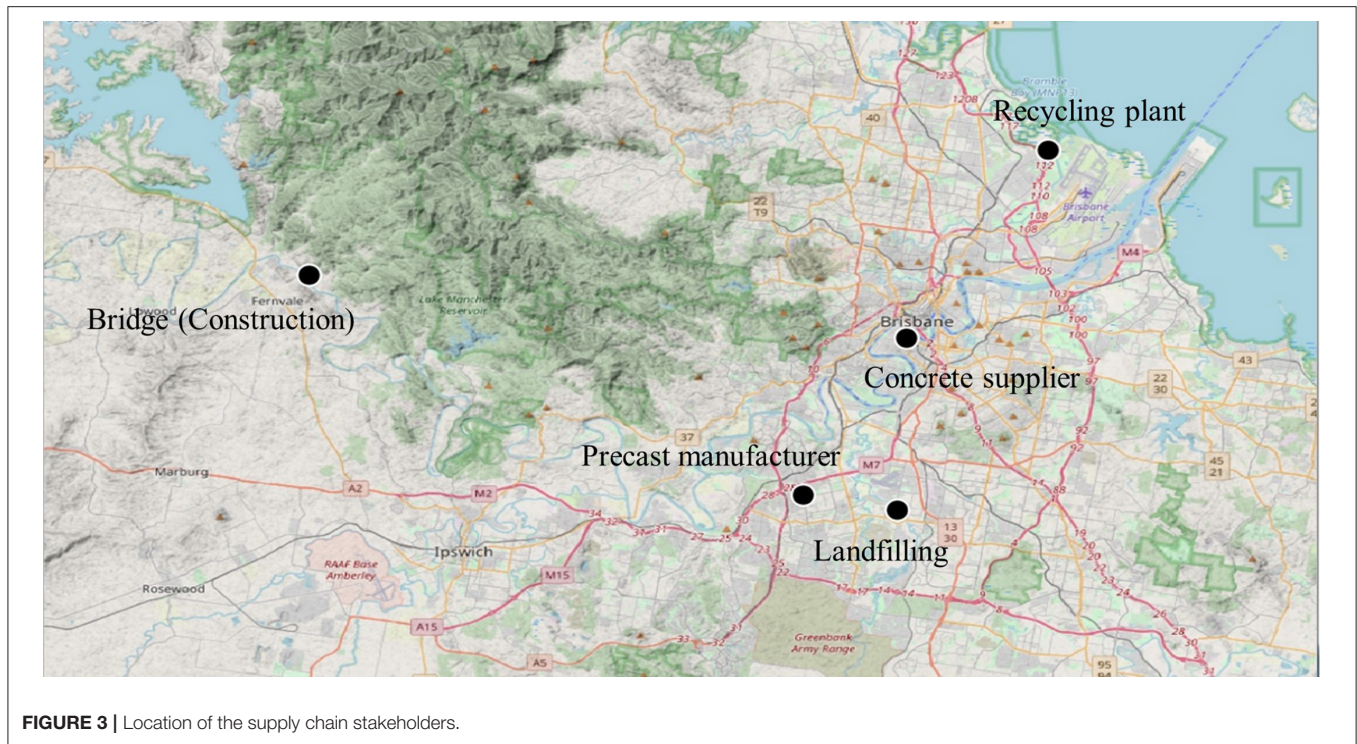


FIGURE 3 | Location of the supply chain stakeholders.

TABLE 2 | Impact of reverse logistics practices on the environment.

Impact category	Unit	Reusing	Rem.	Recycling	Landfilling
Global warming	kg CO2 eq	149,276.89	186,358.53	252,926.02	286,702.07
Stratospheric ozone depletion	kg CFC11 eq	0.02	0.02	0.02	0.03
Ionizing radiation	kBq Co-60 eq	432.46	559.55	-550.93	860.83
Ozone formation, human health	kg NOx eq	523.08	602.99	893.34	927.67
Fine particulate matter formation	kg PM2.5 eq	159.99	174.63	259.11	268.65
Ozone formation, terrestrial ecosystems	kg NOx eq	529.83	610.31	902.80	938.93
Terrestrial acidification	kg SO2 eq	427.80	513.98	689.76	790.73
Freshwater eutrophication	kg P eq	2.74	3.43	3.43	5.28
Marine eutrophication	kg N eq	0.32	0.40	0.45	0.61
Terrestrial ecotoxicity	kg 1,4-DCB	203,420.89	257,633.74	310,237.95	396,354.96
Freshwater ecotoxicity	kg 1,4-DCB	638.63	785.84	936.40	1,208.97
Marine ecotoxicity	kg 1,4-DCB	1,011.43	1,240.15	1,479.67	1,907.90
Human carcinogenic toxicity	kg 1,4-DCB	1,728.80	2,050.76	2,394.17	3,154.97
Human non-carcinogenic toxicity	kg 1,4-DCB	22,227.62	27,358.36	32,942.26	42,089.26
Land use	m2a crop eq	2,316.11	2,949.33	2,770.43	4,537.38
Mineral resource scarcity	kg Cu eq	589.52	746.60	1,076.50	1,148.60
Fossil resource scarcity	kg oil eq	17,847.71	20,828.10	25,061.03	32,042.82
Water consumption	m ³	23,201.83	29,141.95	42,547.49	44,833.23

(2) The bridge is upgraded at the end of 50 years and used for another 50 years (only 30% of new concrete is considered) (Remanufacture).

(3) The bridge components are recycled at the end of 50 years (Recycle).

(The recycling plant of the concrete was assumed to be located 43 km from the bridge, and 30% is recovered as recycled aggregates at the recycling plant).

(4) Use the bridge only for 50 years and landfill waste (Landfill).

(The landfill space was assumed to be located 38 km).

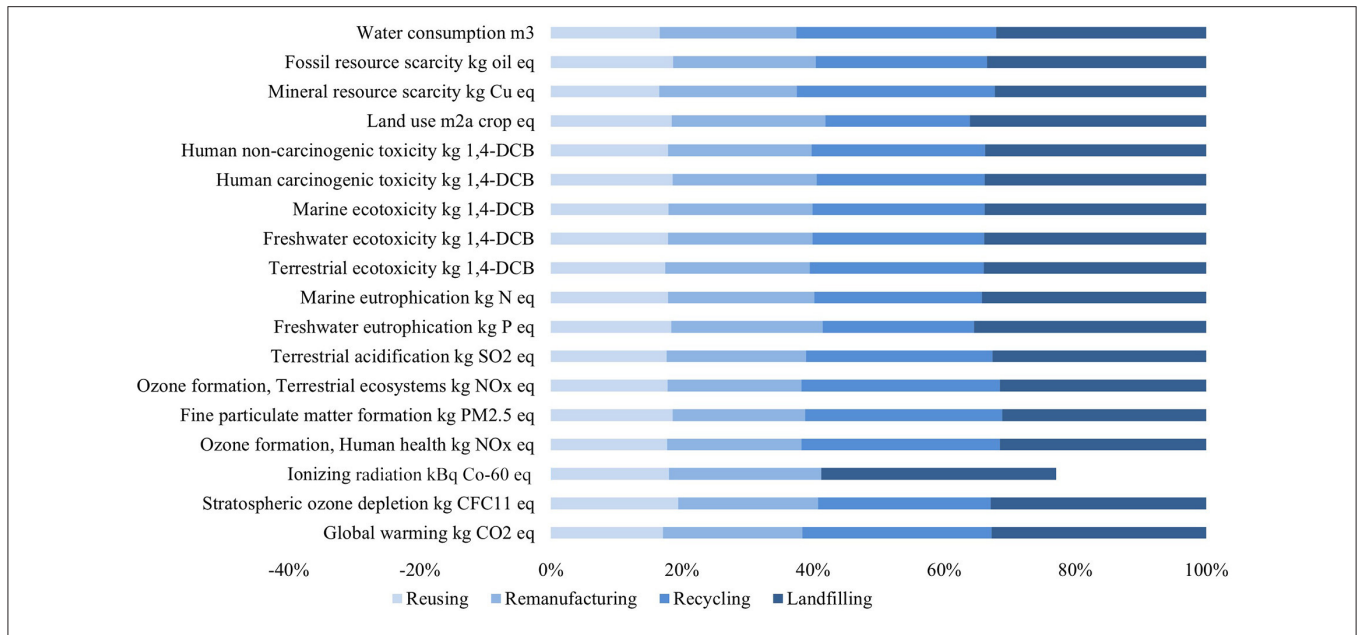


FIGURE 4 | Environmental impact of RL strategies.

TABLE 3 | Impact of reverse logistics strategies on end-point categories.

Damage category	Unit	Reusing	Remanufacturing	Recycling	Landfilling
Human health	DALY	0.31	0.361	0.508	0.555
Ecosystems	species.yr	9.16×10^{-4}	1.14×10^{-3}	1.58×10^{-3}	1.75×10^{-3}
Resources	USD2013	7,112.22	8,203.04	9,658.60	12,619.91

DALY, Disability adjusted life years; species.yr, potentially disappeared fraction of species·m³ year; USD2013, the extra costs involved for future mineral and fossil resource extraction.

RESULTS AND INTERPRETATION

Reusing the concrete of the bridge construction contributes to the least environmental impact, while concrete as landfill contributes to the highest (Table 2, Figure 4). The impact of landfilling is almost double that of reusing; however, recycling contributes to a positive environmental impact in terms of ionizing radiation compared to other strategies (−550.931 kBq Co-60 eq). The reason for this could be that recycling avoids the raising of ionizing radiation through concrete landfilling (Chad-Umoren, 2012). However, the remanufacturing strategy contributes a lesser environmental impact than the recycling process (except for ionizing radiation). These results convey a crucial message to the industry regarding the importance of reusing materials, instead of recycling or landfilling them.

Overall, reusing strategy contributes to < 20% of the overall environmental impact, while remanufacturing, recycling, and landfilling contribute 20%, around 30%, and around 40% of the overall impact, respectively (Table 2, Figure 4). Based on the findings below, it can be further claimed that concrete usage for bridge construction can affect human health and critical ecosystems. At the end point level, landfilling (over 30%) causes the highest damage to human health, ecosystems, and resource availability compared to other RL options, whereas reusing

produces the least damage to the endpoint categories (~17%) (Table 3), and compared to remanufacturing, the recycling scenario has a higher impact on human health, ecosystems, and resource availability.

DISCUSSIONS

Reusing strategy contributes to uppermost environmental benefits, whereas landfilling provides the minimum environmental benefit, and remanufacturing generates more environmental benefits than recycling by reducing damage to human health, ecosystems, and resources availability (Table 3). It is clear that additional efforts must be carried out to adopt options that yield the maximum benefits for the environment and society by the industry decision maker and policy makers. As argued by Pushpamali et al. (2019), Figure 5 depicts that potential RL options yield the most benefits, while landfilling provides the least benefits compared to the efforts taken for implementing such RL strategies. As implied by the LCA results, recycling should be the last option in recovering materials, and distinct mechanisms must be investigated to adopt potentially beneficial approaches. This claim further aligns with the argument that recycling should be the last preference in circular

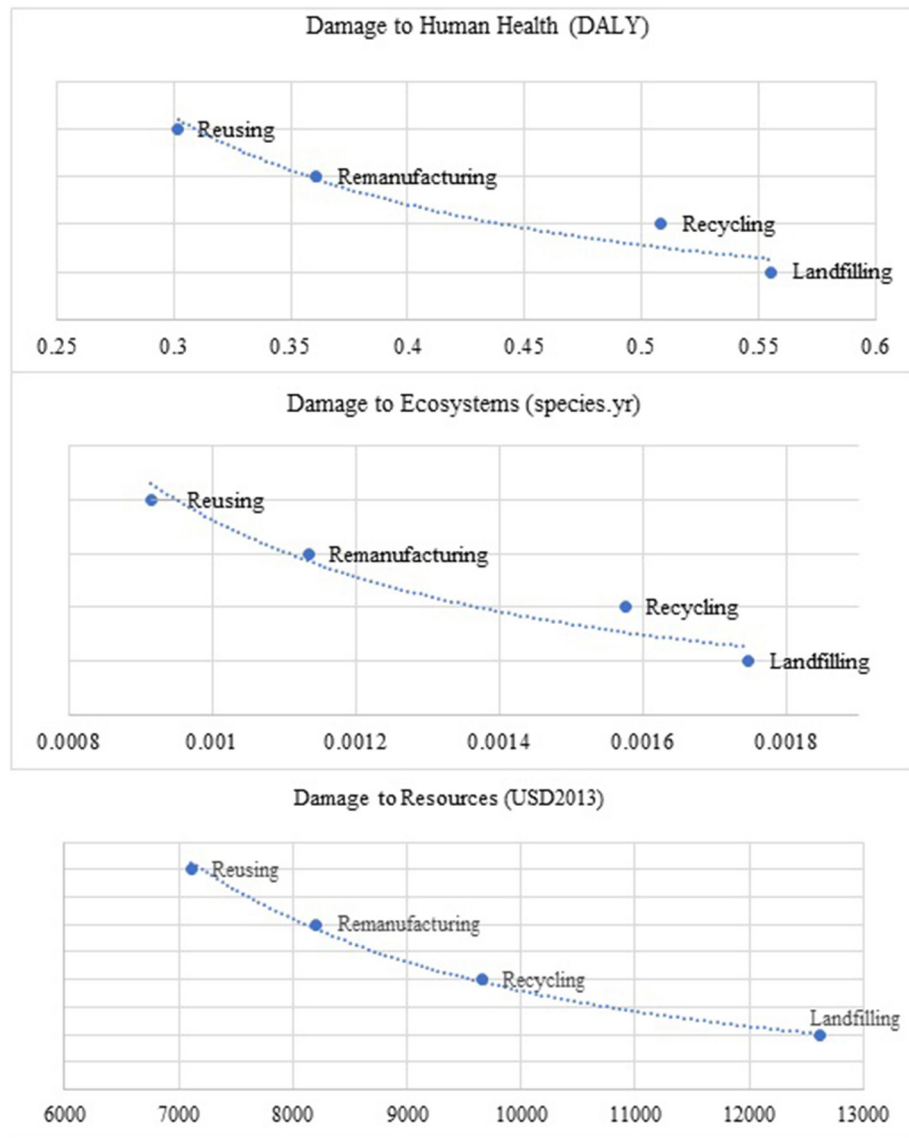


FIGURE 5 | The potential impact of reverse logistics strategies.

economic strategies in an economic system [Ellen MacArthur Foundation (EMF), 2015].

For sustainable infrastructure development, assessing the environmental impact, considering the future natural and human-made disasters, and adding reducing, recycling, and reusing of resources to the design process are important (Ali et al., 2016). Hence, the implementation of RL in construction should be a part of the planning and design stages, as a strategic supply chain decision to obtain long-term environmental, economic, and social benefits. This argument is further illustrated in **Figure 6**. When construction is planned, the type of end-of-life strategy must also be considered at the planning and design stage in addition to other significant requirements. When RL strategies are embedded in strategic decisions, it will reduce cost

(especially the material cost) in the future as the price of used materials is lower compared to the cost of new materials in many situations. Also, making decisions at early stages of the construction process has a higher ability to influence overall cost than making decisions at the later stages (Hendrickson et al., 1989). Further, when materials meet industry specifications, a similar level of quality to new materials might be expected.

Industry stakeholders can play a critical role in facilitating innovative end-of-life strategies (Pushpamali et al., 2020). The government should formulate policies to encourage industry practitioners to consider end-of-life strategies at the design phase and introduce different concession types to encourage industry and the general public. Additionally, designers have a significant role to play as stakeholders in the construction supply chain,

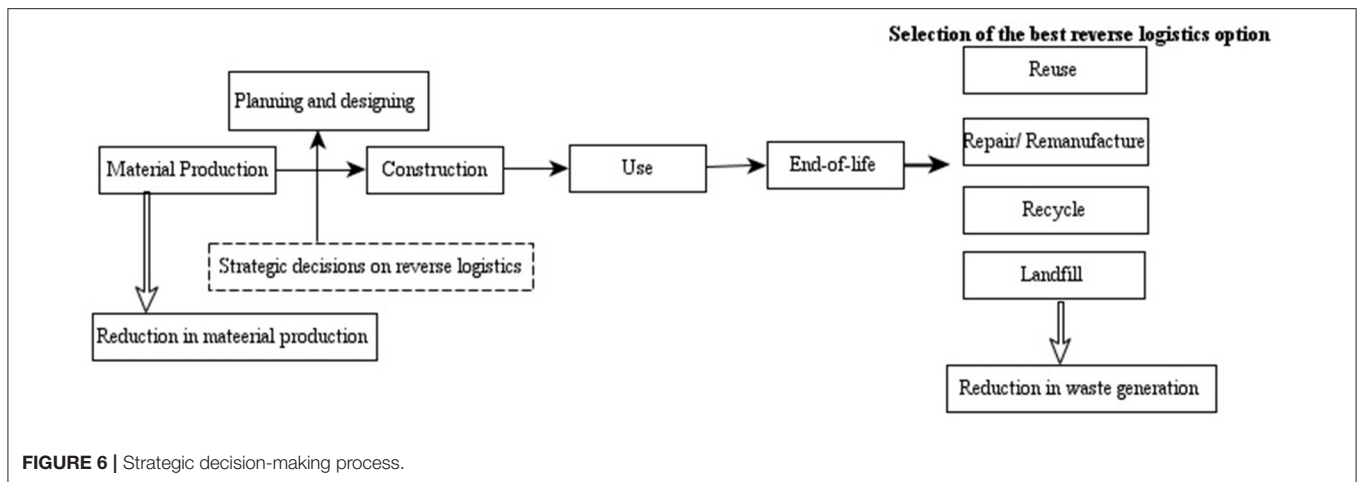


FIGURE 6 | Strategic decision-making process.

need to be more creative and innovative in facilitating end-of-life strategies at early phases to encourage reuse of materials in the future. Further, industry-based researchers and engineers can also play an important role in leading the development of new environmentally friendly RL practices to reduce recycling processes and to find innovative ways to utilize existing materials which require less effort and time. The government, in an institutional support role, can provide further support in the form of research funding and infrastructure to universities to develop new ways to reuse materials.

Design, planning and procurement should facilitate RL because critical changes that assist RL cannot easily be made after commencing a project, and therefore, upstream decision-making is vital for effective RL implementation in the construction industry. This will lead to further reductions in both new material production and waste generation in the long term. From the environmental perspective, although reuse of materials is the best RL scenario, when the RL decision is made, it is wise to consider other critical factors in addition to the environment, such as cost and supply chain performance perspectives to gain the best outcome through RL.

CONCLUSIONS

RL is can be of great benefit to construction industry; however, only recycling is extensively discussed in the construction industry literature related to RL. Recycling is one strategy among other options, and this paper compares different RL options from an environmental perspective with LCA. Although previous literature discusses the importance of RL strategies to the construction sector, there is no previous work that has conducted LCA for different RL strategies across the construction supply chain. This research supports strategic supply chain decision making with respect to RL implementation by comparing different strategies for a realistic case study.

The life cycle assessment results revealed that reuse contributes the least to a negative environmental impact (< 20%) and landfilling (around 40%), the highest in the

midpoint categories, and that reuse and landfilling are the lowest (about 17%) and the highest (over 30%) in endpoint categories, respectively. In summary, reuse and remanufacture have lesser impacts on the environment than other options, as recycling is not the best strategy for recovering materials, even though it is a popular method among industry stakeholders to reduce environmental impact. Consequently, this paper emphasizes the importance of informed strategic supply chain decisions for RL to obtain the best outcome from environmentally friendly practices.

RL decisions should be made at the planning and design stages of a construction project supply chain as a strategic consideration, and it is the responsibility of all the stakeholders in the industry to support early decision-making in order to effectively implement RL. This research addresses a key knowledge gap in the construction industry on the environmental impact of RL strategies from a supply chain perspective. Furthermore, the research implies that the motivation from the practitioners to address this issue, along with supportive design, and more innovative and creative ideas from the researchers, designers, architects, planners, and other actively involved party, are required in this process. As this study was limited to the analysis of only one material (concrete) and one project context (a bridge), additional analysis with a wider range of materials, project types, and influencing factors, in addition to environmental factors, is encouraged.

DATA AVAILABILITY STATEMENT

The data of the study can be requested from the corresponding author for reasonable research purposes.

AUTHOR CONTRIBUTIONS

NP: conceptualization, methodology, writing, and visualization. DA: conceptualization, methodology, writing, and supervision. TR: conceptualization, writing, and supervision. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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