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LIFE CYCLE ANALYSIS OF STRUCTURAL STEEL REUSE USING THE ECONOMIC INPUT-OUTPUT METHOD

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Abstract: Reuse of structural steel is not a new concept in civil engineering. However, even though members, and assemblies of members, have been reused for decades, reuse of steel is not a widely implemented practice. Approximately 90% of demolished steel is recycled and only 10% of that steel is reused in its current state. The structural steel reuse that does occur is due to the reuse of very large members or from specialty projects. The reason for these low levels of reuse is because the cost of reusing structural steel is too high. Unfortunately, many decision makers are coming to this conclusion without a comprehensive knowledge of the true cost of reuse and recycling. In order to fully understand the additional costs, or savings, associated with steel reuse, a life cycle analysis needs to be incorporated into an economic analysis. In this study, the economic input-output method was used to perform a life cycle analysis of structural steel reuse as it compares to current practices. The economic input-output method provides the benefit of being able to facilitate a quick analysis but is limited by only being able to perform a generalized analysis across the entire industry. The analysis was performed for several metrics, which can be grouped into four categories: greenhouse gases, energy usage, water usage, and hazardous waste generation. Results from the analysis show that there is a significant decrease, upwards of 65%, for the calculated metrics across each category for reuse. In order to remedy the limitations of the economic input-output method, it is recommended to perform a similar analysis using a process model approach.

1 INTRODUCTION

Steel reuse shows great promise to become a more “environmentally friendly” alternative to creating new steel from virgin resources and recycled scrap steel. Current practices result in only about 10% of steel being reused as opposed to the nearly 90% of steel that is recycled, but it is believed that this could increase by up to 150% if economic conditions were to change, technological advances were to be utilized, or externalities affecting life cycle cost were considered (Gorgolewski, 2006 and Ness et al., 2014). The impact of a product, process or activity is not only limited to economic impact; there are also environmental impacts and social impacts. Life cycle analysis is a tool used to assess the entire impact of a product, process or activity throughout its entire life cycle. This analysis is a necessary step in the decision making phase of any project. The complete impact of a decision throughout its entire economic life cycle needs to be quantitatively understood in order to properly and knowledgeably make a comparison between proposed alternatives. Performing a life cycle analysis is the only way to truly understand a decision’s full impact, but there are several ways to do this.

2 BACKGROUND

Before being able to quantify the environmental benefits of reusing structural steel, the metrics for assessing environmental impact must be established. These metrics often include carbon footprint, water footprint, and energy use. It is important to note that these metrics need to be determined for the entire life cycle of the process or component and are based on direct and, sometimes more importantly, indirect impacts. A more detailed list of life cycle impacts can be seen in the work of Reijnders (1995), where the focus was on limiting resource use, minimizing pollution, and preserving nature.

2.1 Carbon Footprint

According to Wiedmann and Minx (2008), “… carbon footprint is a measure of the exclusive total amount of carbon dioxide that is directly and indirectly caused by an activity or is accumulated over the life stages of a product.” This definition of carbon footprint does not include any of the other carbon based pollutants or greenhouse gases, such as methane. Wiedmann and Minx argue that this definition is ideal in spite of its limited scope due to its high level of clarity. When selecting a metric for environmental impact it is important that this metric be of significant contribution, clearly defined, and relatively simple to calculate, especially when implementing practices to reduce environmental impact.

2.2 Water Footprint

The industrial sector consumes large volumes of water, but can also pollute even greater volumes downstream (WWAP, 2009). The idea of a ‘water footprint’ associated with each product and process was introduced by Hoekstra (2003) as a very similar concept to ‘virtual water’, originally coined by Allan (1997). Virtual water is the water consumed by the production of every product. It was used in a proposed solution to countries with water shortages by allowing those countries to export their water needs. A water footprint takes this concept a step further by including the water consumed during the entire life cycle of the process or product, rather than just during its production.

2.3 Energy Use

Based on the work by Dincer (1999), energy use is a suitable metric for environmental impact because of the wide range of problems that can be associated with it. Increases in energy use can be correlated to acid rain, ozone depletion, global warming, air pollution, forest destruction, and the production of radioactive materials. This is because many of the bi-products of energy creation have negative effects on the environment. Acid rain is a result of excessive amounts of sulfur dioxide (SO_2), nitric oxide (NO), and nitrogen dioxide (NO_2) being emitted into the atmosphere, which are all released during the combustion of fossil fuels. Ozone depletion is mostly due to chloroflourocarbons (CFCs), which are used in air conditioning and refrigeration units but NO and NO_2 also contribute. Other gases produced during energy production, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and peroxyacetylnitrate, are major contributors to the greenhouse gas effect and global warming.

2.4 The Economic Input-Output Method

The economic input-output (EIO) method for life cycle assessment (EIO-LCA) aims to simplify the process of performing a life cycle assessment without having to limit its scope (i.e. exclude minor products and processes). The EIO method takes an aggregate view of a process or product and determines its life cycle impact based on the resulting inputs and outputs into various industry sectors (Hendrickson, Lave, & Matthews, 2006). For example, in order to construct a reinforced concrete building, a certain quantity of steel reinforcing bars will be required. This steel would represent an output from the steel industry and an input to the construction industry.

The EIO method works by first selecting a product or process to be assessed for its life cycle impact. Next, the entire life cycle requirements for the supply chain of this product or process are determined. These supply chain requirements include everything from extracting raw materials to producing the final product. Once the life cycle supply chain has been established, the discharges associated with each activity in the supply chain are summed and the total life cycle impact is presented. Depending on the desired life cycle analysis output, the aforementioned discharges can be economic activity, environmental, social, etc. (Hendrickson, Lave, & Matthews, 2006).

In order for the EIO method to be feasible, the economy needs to be divided into a limited number of distinct sectors. Each sector also needs to have established and quantified relationships with each of the other sectors. This relationship identifies that amount of inputs required from each sector in order to produce one unit of output for the specified sector. Fortunately, these relationships exist because of the work proposed and carried out by Leontief (1970). The discharges per unit of output from each sector are also required in order to convert the supply chain outputs to a specific type of impact, such as environmental impact. For the specific case of environmental impact, these relationships have already been established (Lave et al. 1995, Hendrickson et al. 1998).

The limitations of the input-output method result mostly from uncertainty as outlined by Lenzen (2001) who listed seven types: (1) source data uncertainty, (2) import assumption uncertainty, (3) estimation uncertainty for capital flow, (4) proportionality assumption uncertainty, (5) aggregation uncertainty, (6) allocation uncertainty, and (7) gate-to-grave truncation error. The data used in the input-output method is collected from national surveys and while errors can be estimated, they cannot be quantitatively known. This results in source data uncertainty. The uncertainty from imports arises because the data associated with foreign goods does not necessarily follow that of their domestic counterparts but the foreign data is not necessarily known. Worst-case errors are typically used to adjust imports but this is a simplified approximation. If capital flow tables do not exist, they must be constructed from capital expenditure from varied sources. This is an approximation and, as a result, a source of uncertainty. The proportionality assumption states that there is a linear relationship between the inputs and outputs and that price is uniform across the economy (Hendrickson et al. 2006 & Lenzen 2001). This means that doubling the output will require doubled input from each input and that the cost of electricity is the same whether being purchased by the steel industry or the fabrics industry. Aggregation leads to uncertainty because multiple producers are combined into a single industry without any way of differentiating between them. The final uncertainty associated with the input-output method is the uncertainty that results from the truncation of the gate-to-grave portion of the life cycle. The EIO method only accounts for the production discharges and neglects any operation, maintenance and end-of-life processes.

3 METHODOLOGY

The life cycle analysis performed in this study was undertaken using the economic input-output life cycle assessment (EIO-LCA) tool, developed by the Green Design Institute at Carnegie Mellon University (CMUGDI, 2008). As discussed previously, the EIO-LCA employs an aggregate overview of the life cycle impacts of a sector of industry based on the desired economic output from that sector. This includes the impacts of other sectors providing inputs to the sector of interest. The methodology for this comparison can be defined by three steps (Figure 1): (1) determining a point of reference, (2) defining appropriate sectors and activities, and (3) equating and comparing equivalent economic activities.

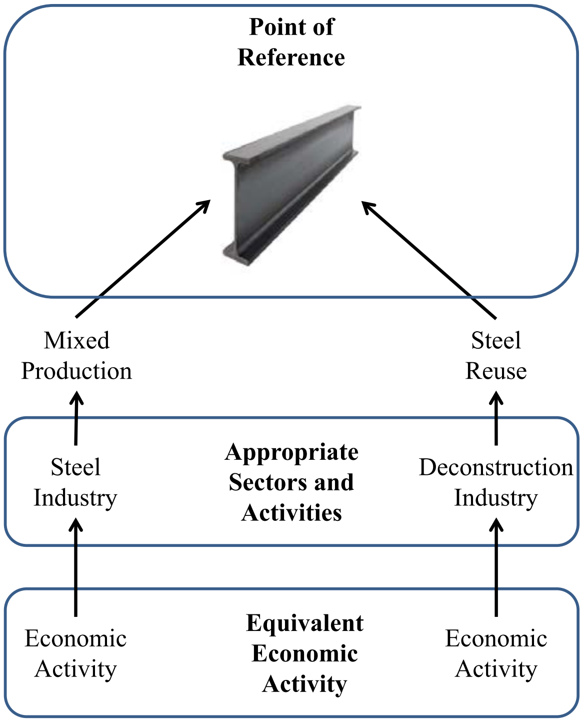

Figure 1: Overview of life cycle analysis methodology

The first step in performing a life cycle analysis is determining a point of reference for the comparison. A life cycle analysis serves very little purpose unless the results are compared with results for another, equivalent alternative. For this study, a particular mass of steel was used as a reference. The exact value for the mass of steel is not important because of the linear nature of the EIO-LCA. Another important consideration for the reference point is where along the supply chain the steel is located. The steel could be located, for example, in the ingot phase, the pre-fabrication phase as an individual member, or the post-fabrication phase, as a member ready for delivery to site. For the purposes of this study, the point of reference was selected as the pre-fabrication phase (PoR1 in Figure 2). This means that the steel has been formed into a standard steel section but has not yet been incorporated into a design or structural assembly, thus no end connections or other such details have been applied. A post fabrication phase point of reference (PoR2 in Figure 2) would also be interesting and may be the subject of a future LCA.

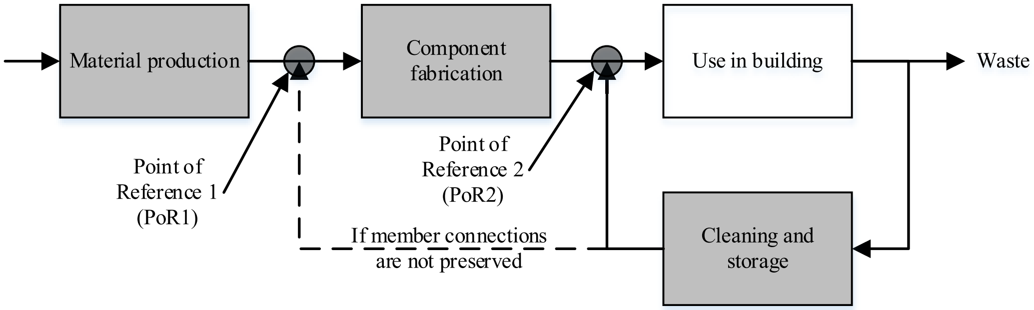

Figure 2: Modified process model for reuse with the life cycle analysis point of reference

The second step of performing the life cycle analysis was to identify the relevant sectors that should be used in the EIO-LCA. The data set used for the analysis was the USA 2002 Benchmark (CMUGDI 2008). This is comprised of 428 different sectors and contains the cradle-to-gate interactions required to produce outputs from each of these sectors. Cradle-to-gate means that the life cycle analysis is only complete to the point where the desired output is produced, for example when a steel ingot is produced at the foundry. The production of new steel components was assumed to come from the “iron, steel pipe and tube manufacturing from purchased steel” sector. This is responsible for the production of welded and rolled structural steel shapes (CMUGDI, 2008). The production of reused steel components was assumed to come from economic activity in the demolition industry. Unfortunately, demolition is not a sector included in the USA 2002 Benchmark data so construction of nonresidential manufacturing structures was selected as a surrogate. It is reasonable to consider construction and deconstruction as equivalent processes performed in an opposite manner. Many of the activities in this sector would be present in the removal of structural steel from buildings at the end of their service life. The main difference is that the deconstruction processes also includes activities for steel and cement manufacturing. The activity in these sectors would be present for the case of construction activity but would likely be absent from reuse activities. An adjustment was made to the impacts of the nonresidential manufacturing structures sector by removing the impacts that result from steel and cement manufacturing. With these sectors removed, the impact results will be more representative of reuse activities. For example, Table 1 displays the five highest total energy using sectors required to produce economic output from the “nonresidential manufacturing structures” sector. It is reasonable to presume that a large majority of the energy usage from “Iron and steel mills” would not be required, and can therefore be disregarded, if the structural steel is being reused.

Table 1: Highest energy users from the “nonresidential manufacturing structures” sector

Sector Name	Total Energy Usage (TJ)*
Nonresidential manufacturing structures	2.39
Power generation and supply	1.14
Iron and steel mills	0.40
Petroleum refineries	0.26
Truck transportation	0.14

*values are reported per $1,000,000 of economic output

The final step was to determine the economic output from each sector required to achieve the desired mass of steel as specified in the first step. In order for a meaningful comparison to be made, the end production of each process needs to be the same. This means that the mass of steel that results from current practices and reuse need to be the same. Unfortunately the EIO-LCA method uses economic activity as the scale defining parameter for the analysis so equivalent economic activities for each production method needed to be calculated. The conversion values used in this study can be found in Table 2.

Table 2: Mass to economic activity conversion rates

Production Method	Conversion Rate
Current Practices	$3.64 / kg
Reuse	$4.93 / kg

The current practices conversion rate of $3.64 / kg was selected based on the average material price of structural steel sections ranging from 200 mm to 350 mm in depth. The unit prices for these sections were obtained from RSMeans (2009). The reuse conversion rate was selected as $4.93 / kg. This value was based on the average construction cost per unit mass of various industrial steel framing structures. Following similar logic to the selection of the sectors from USA 2002 Benchmark data, the cost of constructing a particular mass of steel is equivalent to deconstructing that same mass. These unit prices were also obtained from RSMeans (2009). Neither price was adjusted for inflation or changes in market value. The accuracy of this study would be increased if current prices were used, but this was deemed unnecessary for this investigation. Together, these values create a new steel to reused steel price ratio of 1:1.35. This comparison is based on the assumption that the steel is in a pre-fabrication state, as previously stated. It is expected that reused structural steel closer to the installation stage of the supply chain (PoR2 in Figure 2) would result in a more favourable price ratio.

4 RESULTS

The metrics for the previously described comparison were divided into five distinct groups: conventional air pollutants (Figure 3), greenhouse gases (Figure 4), energy consumption (Figure 5), water usage (Figure 6a), and hazardous waste production (Figure 6b). The reported results are based on $1,000,000 of new steel production. A description of each metric can be found in Table 3.

Table 3: Definition of metrics used for life cycle analysis

Metric Name	Description
CO	- carbon monoxide emissions into the atmosphere
NH_3	- ammonia emissions into the atmosphere
NO_x	- oxides of nitrogen emissions into the atmosphere
PM_{10}	- particulate matter emissions into the atmosphere with diameter less than 10 microns
$PM_{2.5}$	- particulate matter emissions into the atmosphere with diameter less than 2.5 microns
SO_2	- sulfur dioxide emissions into the atmosphere
VOC	- volatile organic compound emissions into the atmosphere
CO_2 Fossil	- carbon dioxide emissions into the atmosphere from fossil fuel combustion only
CO_2 Process	- carbon dioxide emissions into the atmosphere from all processes other than fossil fuel combustion
CH_4	- methane emissions into the environment
N_2O	- nitrous oxide emissions into the atmosphere
HFC/PFCs	- hydrofluorocarbons, perflourocarbons, and sulphur hexafluoride emissions into the atmosphere
Coal	- energy consumed from coal sources
NatGas	- energy consumed from natural gas sources
Petrol	- energy consumed from petroleum sources
Bio/Waste	- energy consumed from biomass or waste sources
NonFossElec	- energy consumed from non-fossil fuel electric sources
Water Withdrawals	- water withdrawn from the environment
Hazardous Waste	- the amount of hazardous waste generated as defined by the Resource Conservation and Recovery Act

Figure 3 through Figure 6 show that, typically, the analysis for structural steel reuse results in significant life cycle impact reduction. Only four out of the 19 metrics investigated resulted in a significantly increased impact due to the reuse process. Table 4 quantifies the comparison of each metric as the percent reduction that results from applying reuse processes as opposed to current practices. Although a benefit is not demonstrated in all metrics of this study, a generalized decrease in the environmental impact can be seen as a result of reuse. The total mass of conventional air pollutants was reduced by 0.25 t, or 1%, the total mass of greenhouse gases in CO_2 equivalent was reduced by over 1500 t, or 75%, and the total energy usage was reduced by over 17 TJ, or 69%.

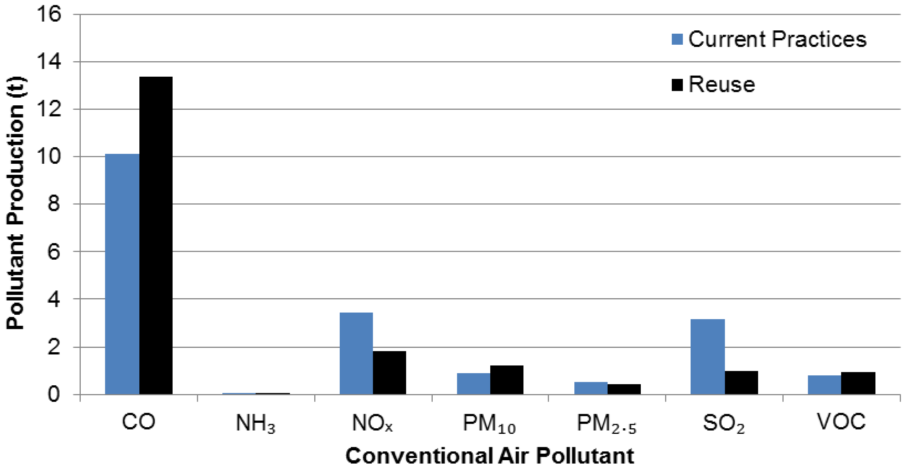

Figure 3: Life cycle analysis comparison between current practices and reuse for conventional air pollutants

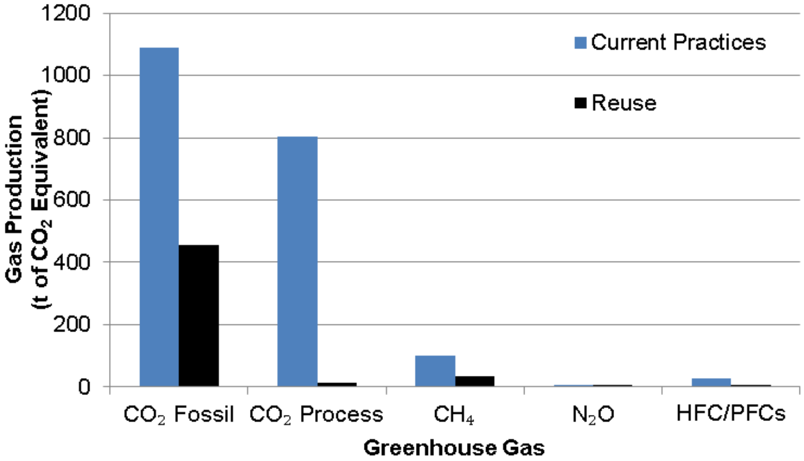

Figure 4: Life cycle analysis comparison between current practices and reuse for greenhouse gases

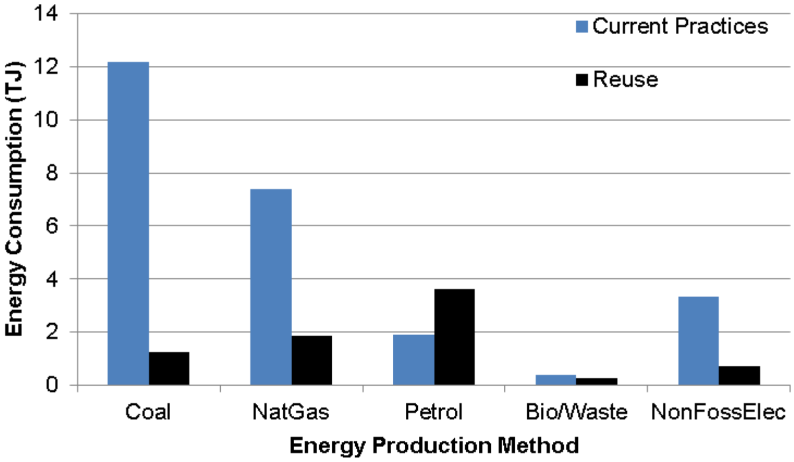

Figure 5: Life cycle analysis comparison between current practices and reuse for energy consumption

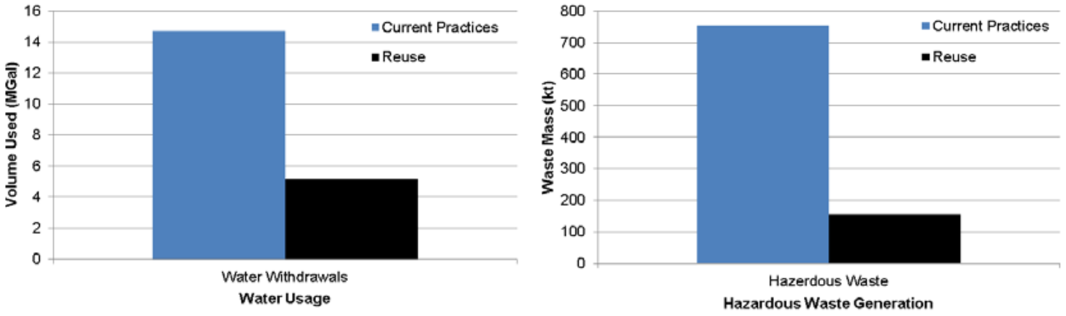

Figure 6: Life cycle analysis comparison between current practices and reuse for water usage (a) and hazardous waste generation (b)

Table 4: Percent reduction of life cycle assessment metrics as a result of reuse

Life cycle assessment metric	Percent reduction as a result of reuse*
CO	-32%
NH_3	47%
NO_x	47%
PM_{10}	-32%
$PM_{2.5}$	20%
SO_2	69%
VOC	-20%
CO_2 Fossil	58%
CO_2 Process	98%
CH_4	65%
N_2O	6%
HFC/PFCs	77%
Coal	90%
NatGas	75%
Petrol	-90%
Bio/Waste	36%
NonFossElec	78%
Water Withdrawals	65%
Hazardous Waste	79%

*negative percent reductions indicate an increase as a result of reuse

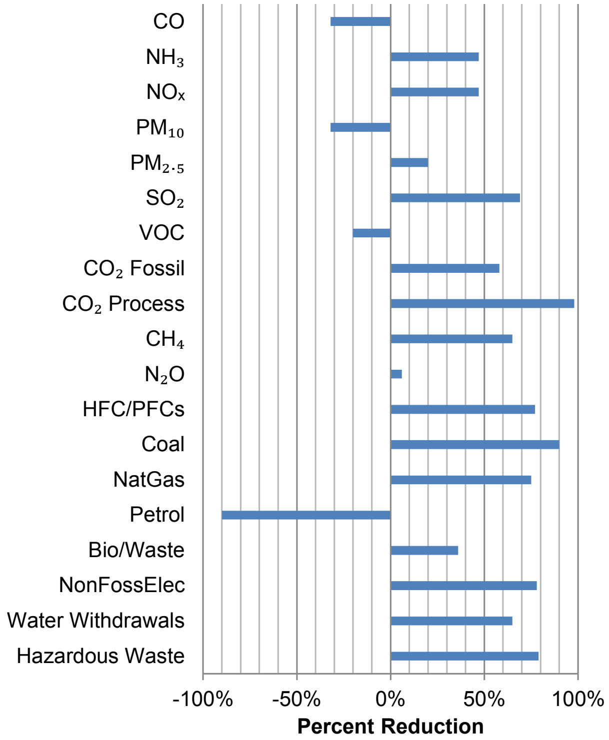

Figure 7: Percent reduction of life cycle assessment metrics as a result of reuse

5 DISCUSSION AND CONCLUSIONS

The economic input-output life cycle analysis results show a clear indication that reuse has the potential to provide significant benefits over current practices. Steel reuse exhibited superior results in nearly every presented metric, given the parameters of this study. When the results are generalized, a 75% reduction in greenhouse gases and a 69% reduction in energy use is expected for steel reuse.

The external costs associated with construction decisions, such as material source, are not often considered in current decision making practices. These costs are not considered because they are not accurately understood and they are not associated with direct costs to the decision maker. Introducing direct costs to the decision maker, through carbon credits for example, would encourage practices that incorporate a broader, societal cost into their decision making process. This work makes progress towards achieving accurate quantification of the societal cost of reuse practices but more work is still required.

6 FUTURE WORK

One of the main drawbacks of the EIO-LCA method is its aggregate scale. This prevents the specific processes, such as the reuse process, from being examined directly. As a result, a number of assumptions and simplifications needed to be made. These assumptions and simplifications may have an impact on the results. As such, these results should only be treated as preliminary.

A more detailed analysis is essential for accurately quantifying the benefits or costs of reusing structural steel. For this analysis, it is recommended to replace the aggregate approach used by the economic input-output method, with a more detailed approach, such as the process model approach.

It is also worth investigating how the externalities identified in this EIO-LCA could be monetized, such as carbon credits, so that the opportunity cost to society of not reusing steel could be understand and could influence future reuse decisions.

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