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# Towards the prediction of carbon consequences in early design decisions

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**Abstract**

Manufacturing processes and associated supply chains are a recognised source of carbon emissions. In part these emissions are related to the design of the product itself. For example, decisions surrounding the selection of materials have a high impact on emissions and hence the embedded carbon in manufactured products. While there are tools that support the analysis of designs from environmental perspectives, they tend to require near complete design descriptions that are only available later in the design and development process when time and scope for change is limited, e.g., by scheduling and cost constraints. Further, there are often trade-offs to be made. For example, decisions related to the selection of materials impacts the embedded carbon of resources needed to manufacture a product but may also have a knock-on effect on transport and associated carbon emissions.

This paper reports early work exploring the feasibility of establishing engineering design tools that are suitable for use early in the design process when the design definition is incomplete and there is scope for exploring a wider range of design options. An illustrative case study was used to consider the quantification of carbon costs associated with material selection and associated transportation. Discrete event simulation models were derived from early design descriptions coupled with a range of alternative material and supply chain scenarios. Early results are promising in that they can be used to compare carbon consequences of alternative design directions.



*Keywords:* Carbon Emissions; Product Structure; Engineering Design; Early Design Decision; Visualisation Tool

## 1. Introduction

Environmental sustainability is an important issue, especially for manufacturing industries where increasing environmental awareness has affected global markets [1]. Minimising carbon emissions of manufacturing industries, which Karthick & Uthayakumar [2] identify as a major source of global carbon emissions, is critical in achieving environmental sustainability and so the United Nations' Sustainable Development Goals. Design is a critical step to improve environmental sustainability. For example, Delaney et al. [3] provide a review of design methods for environmental sustainability and Belucio, et al., [4] highlight the importance of decisions made early in design processes. This paper reports early research exploring ways in which engineering design organisations might improve the environmental sustainability in their engineering supply chains.

Environmental sustainability can be quantified in many different ways. The focus of this paper is on carbon emissions from manufacturing: one of the largest contributors to greenhouse gas emissions worldwide. Reducing $CO_2$ emissions in manufacturing by allowing them to be considered as part of the design process has the potential to produce notable benefits. However, predicting carbon consequences of design decisions remains challenging and only a small number of methodologies used by previous researchers are available. A critical aspect of all such methods is the selection of an appropriate system boundary due to its significant impact on the carbon emissions calculation [5]. For example, globally, different materials have different sources meaning that, in addition to carbon emissions associated with material extraction, there are also emissions associated with shipping of


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materials from their source to the location of the manufacturing process. For this reason, this paper includes within its scope both raw material selection which is typically done in response to design requirements [6] but also has embedded carbon emissions, (e.g., as shown in Table 1) and associated transportation processes (recognised by the US Environmental Agency as increasing carbon footprints by over 20% [7]) with a view to incorporating carbon emissions in early design decisions. It should be noted that, although specific suppliers are likely to be selected later in the product development process, the need to transport materials from their source to the location where they will be used remains, meaning that estimates of likely impact can be made early in the process. In addition, at this stage of the research it is assumed that new materials are to be used although, in principle, there is no reason why recycled materials from sources local to manufacturing could not be included provided data on embedded carbon of the recycled materials was available.

This paper explores the feasibility of providing tools for use by engineering designers, who typically have limited supply chain knowledge, to visualise the implications of early design decisions on risks to environmental sustainability of engineering supply chains. Given the wide scope of environmental sustainability, both in terms of how it might be quantified and the extent of the supply networks considered, this research focussed on net zero carbon emissions in material supply for manufacturing but not the transport that is part of the manufacturing process itself. In the next section, major research areas of environmental sustainability within product design are discussed followed by the importance of early decision making on environmental sustainability in engineering supply chains. Finally, methodologies used by previous researchers to quantify carbon emissions are reviewed. Action Design Research was the methodology used for the research; this is explained further in Section 3. A design case study was used to validate the research method and is introduced in Section 4. Section 5 shows the outcomes of implementing the case study using the research method. Results are discussed in Section 6 and conclusions drawn in Section 7.

## 2. Background

Environmental sustainability prioritises environmental life support systems where the health of all ecological components e.g., water, air and soil, must be maintained [8]. Delaney, et al., [3] argue that the sustainability of product development processes is greatly influenced by the design of the product. According to Delaney, et al., there are 17 major research areas of environmental sustainability in relation to product design which are recognised as contributing to the environmental sustainability of a product. For the purpose of this research, two aspects were considered: material selection and transport. According to Delaney, et al., a typical design process consists of six key stages: preparation, concept design, embodiment design, detailed design, design finalisation and planning and production. Further, they suggest that the focus should be during the detailed design phase as at this phase specifications and quantitative data are clearer which helps in exploring opportunities for environmental impact reduction [9]. However, by this stage in the development of a product, the scope for change is limited, e.g., by cost and schedule constraints. For this reason, this paper explores the feasibility of considering carbon emissions earlier in the design process, during concept design. In the early design stages of a product, engineering designers evaluate alternative designs and assess trade-offs between factors that influence the delivery of design requirements which, increasingly, include requirements related to environmental sustainability [10]. A key concept in encompassing manufacturing and environmental aspects, to promote efficient use of resources and lower emissions, is to include eco-efficiency in early design decisions [4]. Examples of environmental aspects that need to be considered early in the design process include primary manufacturing processes, raw material selection and transport. Belucio, et al., [4] asserts that life cycle analysis has been practiced to support decision-making, developing greater potential in minimizing environmental impacts and costs at the early design phase. Early design planning is typically practiced in supply chain management but primarily focusing on minimising operational costs, ensuring product quality and preventing operational risk. The UN's Sustainable Development Goals encourage engineering industries to start implementing environmental sustainability in their engineering supply chains. Improving sustainability in manufacturing by minimising carbon emissions has the potential to produce notable benefits for the future. Given the wide range of factors that impact emissions, this paper focusse on two: material selection and transport within manufacturing supply chains.

Life Cycle Analysis (LCA) methods are the most widely used approaches to calculate carbon emissions of engineered products. A variety of methods for LCA have been proposed by previous researchers. Wang, et al., [11] analyse carbon footprints based upon the concept of product life cycle, by dividing it into five stages: (i) extraction of raw materials, (ii) manufacturing, (iii) transport, (iv) usage and (v) recycling. Their method is specific to a gear hobbing machine and is impracticable for application to different situations because the method is based on design features that are specific to gear hobbing. Priarone & Ingarao [12] discuss the modelling of life-cycle energy demand and carbon emissions in four life cycle stages: material production, manufacturing, transport and usage. The authors focus on the differential impact of life cycle energy demand and carbon emissions on metal-based components produced by subtractive and additive manufacturing. Zhang, et al., [13] propose a quantification for variable carbon emissions of mechanical parts from raw material acquisition, manufacturing and usage with a focus on integrating material and structural optimisation of mechanical parts to produce low-carbon designs of structural components. According to the authors, mechanical parts consume high amounts of energy and resources in the manufacturing stage and hence produce large carbon emissions. This method is more suitable in calculating carbon emissions for structural components later in the development process, rather than engineering supply chain processes earlier in the development process, because it needs data related to the design of modular buildings which cannot be easily identified at early stage of the design.

Song, et al. [14] discuss carbon chain structures in supply chains. Similar to Wang, et al. [11], the authors define the supply chain as consisting of raw material extraction, production and manufacturing, transport, usage, and disposal & recycling. Using the idea of a carbon chain structure, the authors introduce a decision-making method based on a mathematical approach where quantitative analysis is made based on existing data and evaluation from experts. This method is ideal for engineering supply chain processes but needs more input data in determining the supply chain boundaries. Zhou, et al. [15] introduce a carbon emissions calculation model for material, energy and waste in part machining processes. They derive material carbon emissions from (1) raw materials, (2) cutting tools and (3) cutting fluid consumed in a manufacturing process stage.

To summarise, a number of different methods are proposed to calculate carbon emissions. However, each method requires different input information and produces different kinds of results. Further, some methods include the calculation of carbon emissions at different life cycle stages (though there is limited agreement on what these stages are) whereas others (e.g., Wang, et al. [11]) propose the use of screening conditions. All of the methods reviewed relate to life cycle stages of physical products which, ultimately, are defined by geometric definitions and material specifications. Engineering supply chains, on the other hand, are defined by supplier organisations and the processes that connect them to form a supply chain or network. While these processes can be mapped into life cycle stages of products, it does not necessarily follow that the methods reviewed are applicable to supply chains. According to Hao, et al. [16], it is difficult to define distinct relationships between performance metrics and design variables in engineering industries. In response, to evaluate the consequences of different design decisions on supply chain performance, engineering simulation was coupled with existing methods for calculating carbon emissions. To accommodate environmentally-focussed product design, engineers and designers need assessment tools to promptly compare prospective products' environmental performance [17]. In this paper, a method is introduced to calculate the carbon emissions related to material selections and transport in manufacturing supply chains, where data requirements for the calculation can be obtained at an early design stage.

## 3. Research Approach

The research focused on the quantification of carbon emissions in two key processes: material selection and transport of raw materials to location of the primary manufacturing process. The method used for the research involved a combination of Action Design Research (ADR) and Case Study research. ADR is an Action Research method integrated with the design of prototypes, in our case software prototypes, which are used for producing new understanding [18]. There are four stages of the ADR method. Review of literature is the first stage of ADR method (see Section 2). The next stage is building, intervention and evaluation (BIE). The building [of software prototypes] started with the creation of a framework for estimating carbon emissions in manufacturing processes, alternative manufacturing scenarios and key parameters for calculation of embedded carbon in a given design. For this research, discrete-event simulation was used to model supply chain transport process.

From the literature review, current practice in quantification of carbon emissions in engineering industries was analysed and used to inform the framework developed for estimation of carbon emissions in manufacturing processes. The framework provided an underlying structure to support the research and helped to address different manufacturing scenarios. Key parameters were included for the calculation of embedded carbon. The ADR method aided generation of design knowledge regardless of the fundamental design-make scenarios, where the engineering software prototype was implemented as a form of evaluation tool for the research. The prototype was used to challenge the assumptions and knowledge from the literature review and quantify carbon emissions resulting from different combinations of supply chain structure and material. The resulting solution integrated three software packages: one for discrete event simulation of the supply chain processes (Witness), another for shape modelling (SolidWorks) and a third for evaluation of material properties (ANSYS EduPack).

Discrete-event simulation identifies changes in simulated processes as the simulation progresses over time [19]. This research required data in terms of the distance travelled, hence the time attribute was used to represent the distance. A triangular distribution was implemented as the time attribute and according to Lanner [20], this distribution is used when it is difficult to acquire statistical data on the area under study, but the expected range of values and the most common value are known. To represent the distance goods are transported, 1-time unit of the part in simulation cycle was equivalent to 10 km. Simulation models were built based on the following assumptions: (1) only local suppliers are involved in external design, make and assembly processes; (2) a given part has the same shape and dimensions for each material used; (3) all parts are transported by 3.5 tonne HGV with the load limit of 1000 kg; (4) the weight of the HGV is not included in calculation.

The approach to the calculation of carbon emissions related to material selection and transport was adapted and derived from the analysis of methods introduced by Song, et al. [14] and Wang, et al. [11] and is shown in Equation 1. This equation was introduced to calculate the carbon emissions related to material selections and transport in manufacturing chains. The equation is not related to a specific type of product so could be used for different product case studies. In addition, the data needed for the calculation can be obtained at an early design stage. The required data were mass of product, distance travelled, and carbon coefficient of the materials, which was taken from ANSYS EduPack and carbon coefficient of the transport, which was taken from UK Government GHG Conversion Factors. SolidWorks was used to calculate the mass of the product. Five materials were selected for this research: stainless steel, aluminium, titanium, ABS and nylon. The carbon coefficients for material and transport are shown in Table 1.

$$CE = \sum m_{part} c_{material} + \sum d_{total} c_{transport} m_{part} \quad (1)$$

where
$CE$ is the carbon emission ($kgCO_2e$)
$m_{part}$ is the mass of the part ($kg$)
$d_{total}$ is the total distance travelled ($km$)
$c_{transport}$ is the carbon coefficient for transport ($kgCO_2e/tonne-km$)
$c_{material}$ is the carbon coefficient for material ($kgCO_2e/kg$)

Table 1. The carbon coefficient. Reproduced from ANSYS EduPack and [21]

| Materials | Carbon Coefficient ($kgCO_2e/kg$) | Transport | Carbon Coefficient ($kgCO_2e/kg$) |
|---|---|---|---|
| Stainless Steel | 4.91 | HGVs | 0.0259 |
| Aluminium | 13.69 | Vans | 0.147 |
| ABS | 3.41 | Domestic Cargo Flight | 2.20 |
| Titanium | 17.67 | General Cargo Ship | 0.0161 |
| Nylon | 6.09 | Rail | 0.0278 |

## 4. Case Study

An existing test case was used as an example for this research: a torch consisting of upper body, lower body, bulb, bulb housing, lens and lens retaining ring. There were two product structures, shown in Fig. 1 (a) and (b), and four design-make scenarios for each product structure, as shown in Table 2, were used. The simulation models representing supply chain processes that mirror product structures A and B are shown in Fig. 2 and were developed using Witness. To calculate carbon emitted from transport in the supply chain, the transit time for each part was required.

a

| Tier 0 | Tier 1 | Tier 2 |
|---|---|---|
| Torch | | |
| | Bulb Housing | |
| | | Bulb |
| | | Bulb Housing |
| | | Lens |
| | | Lens Retaining Ring |
| | Torch Body | |
| | | Upper Body |
| | | Lower Body |

b

| Tier 0 | Tier 1 | Tier 2 |
|---|---|---|
| Torch | | |
| | Bulb | |
| | Bulb Housing | |
| | Lens | |
| | Lens Retaining Ring | |
| | Torch Body | |
| | | Upper Body |
| | | Lower Body |

Fig. 1. (a) product structure A; (b) product structure B

Table 2. Scenario for Each Product Structure

| Scenarios | Descriptions |
|---|---|
| 1 | Parts were designed and made in-house, and the sub-assembly was assembled in-house |
| 2 | Parts were designed and made in-house, and the sub-assembly was assembled externally |
| 3 | Parts were designed and made externally, and the sub-assembly was assembled in-house |
| 4 | Parts were designed and made externally, and the sub-assembly was assembled externally |

Witness simulation was selected for the simulation models built for each scenario. The simulation models representing supply chain processes that mirror product structures A and B are shown in Fig. 2. To calculate carbon emitted from transport in the supply chain, the transit time for each part was required.

## 5. Results

The simulation model was run for batch sizes of 1000. Five materials were selected; for each material, and given Assumption 2, the torch had a different mass. The mass was taken from the Mass Properties element in SolidWorks and is shown in Table 3. In line with other assumptions, the torches were transported locally using a 3.5-tonne HGV where the carbon coefficient was 0.02599 $kgCO_2e/tonne - km$ [21].

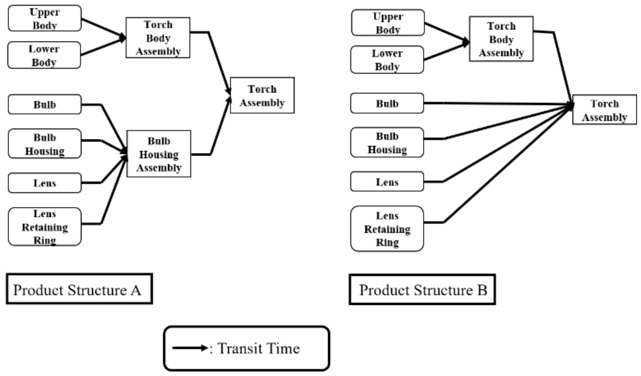


Fig. 2. Simulation models for supply chains corresponding to the alternative product structures in the case study

Table 3. Mass of 1000 unit of torch for different materials

| Materials | Mass (kg) |
|---|---|
| Stainless Steel | 491.6 |
| Aluminium | 172.7 |
| Titanium | 281.6 |
| ABS | 61.8 |
| Nylon | 79.5 |

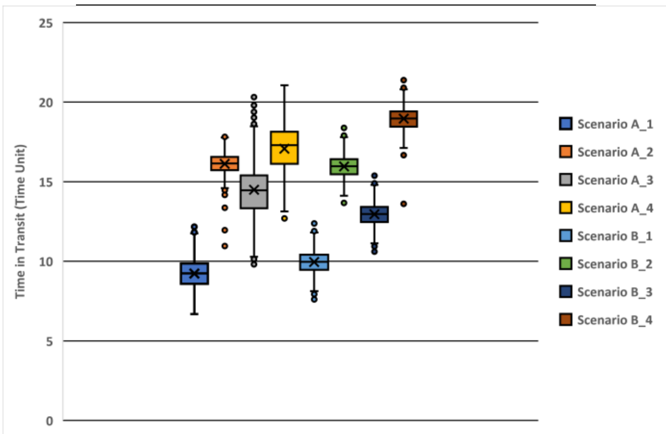


Fig. 3. Time in transit for 1000 unit of torch

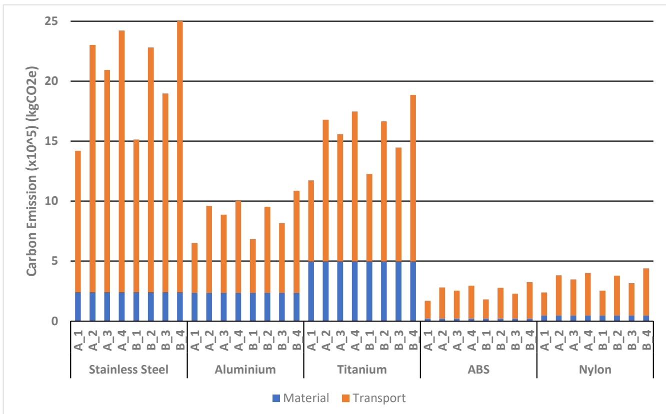


Fig. 4. Carbon emissions for material selection and transport for each scenario

The time in transit for 1000 units of torch is shown in Fig. 3. From the data obtained, carbon emission was calculated by using Equation 1 and the result is shown in Fig. 4. Fig. 4 shows the carbon emissions determined for material selections and transport. From the graph, ABS produced the least amount of carbon emissions. Regardless of the manufacturing scenarios, the carbon emissions related to materials did not change, since the mass of the 1000 torch units was the same for each material. For transport, the carbon emissions varied for each scenario. This indicates that, for a given material choice, supply chain and hence the product structure has a significant impact on carbon emissions.

## 6. Discussion

This research addressed a knowledge gap related to the prediction of carbon emissions, or risks thereof, during early product design and development when scope for change is at its highest but information related to the design is at its lowest. Given the scale of the problem, we focussed on a fragment of the material supply chain (from material supplier to lowest tier manufacturer) and just two performance indicators: carbon emissions involved in the production of the primary raw material (e.g., from bauxite ore to aluminium metal) and likely emissions in transportation of the raw material to the first tier of the manufacturing supply chain. In this way, in the longer term, this will enable engineers to make emissions-based trade-offs between material processing costs, indicated by carbon coefficients, and likely transportation costs (e.g., emissions related to sea and road transport, and the distances to be travelled). The early results reported here show that early design decisions can have a significant impact on the carbon emissions. Exploring the feasibility of considering carbon emissions at an early design stage can be costly [22] but, in the future we envisage integrating learning from this research with other work [22] that takes account of design architectures and their impact on the design of engineering supply chains.

By referring to Fig. 4, the carbon emissions to transport 1000 torch units has a bigger impact compared to the carbon emissions of material selection to manufacture the torch. It is a common occurrence in engineering industries where the mass of products transported is heavier than the mass of product case study used for this research. This would significantly affect the carbon emissions which also affecting the carbon cost of transport. The product structures also influence the carbon emissions, which by referring to Fig. 4, scenarios 1 and 3 produced lower carbon emissions compare to scenarios 2 and 4. In this case, it can be determined that the in-house sub-assembly is better than external sub-assembly. Like any product, the case study used in this paper can be described in multiple ways. For example, two BoMs, each with a different structure, are shown in Fig. 1. The design BoM (product structure A), as is typical in many engineering organisations, the structure of the design BoM is governed primarily by function and the engineering BoM (product structure B) has a structure that reflects the assembly. The simulation model reported in this paper covered transport and production of the non-standard parts (i.e., the bulb housing and the two torch body parts) and showed the way in which different design decisions impact carbon emissions.

Fig. 5 shows the graph analysis for product quantity, mass of product (according to materials and during transport) to the carbon emissions. The y-axis of the graph is the carbon emissions and the x-axis is the product quantity. From the graph, it shows that the mass of product increases when the product quantity increases. As for the transport, the graph shows that the carbon emissions to transport the products is the

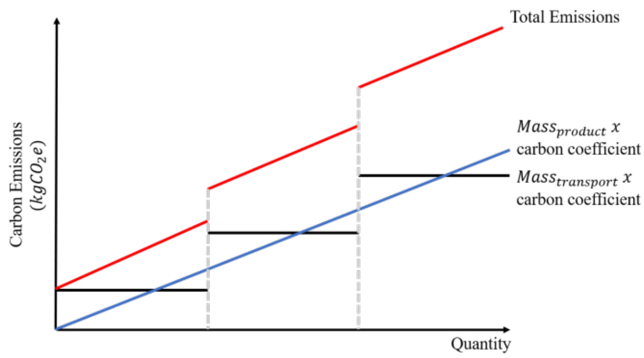


Fig. 5. Schematic representation of the change in carbon emissions with product batch size

same until the maximum gross weight limit is reached. Once the weight limit is reached, there will be an increment in the carbon emissions since additional transport is required.

The carbon data considered in this research include type of raw materials, locality of the supplied materials i.e., the UK, mode of transport and gross and net weight of the shipment. To indicate the carbon emissions, for whole products, there will be a need to integrate specific component data with that for standard parts so creating a measurement for data on carbon emissions with provenance and details of evaluation to ensure comparisons are valid. There are boundaries in creating the simulation models. First, the models are considered to be manufactured in the UK. For the purpose of this research, the external suppliers and manufacturers were within the same region. Second, the HGV was only transporting the materials and parts for the manufacturing of the torch. The net weight of the HGV was not included in calculating the carbon emissions. Lastly, regardless of the material selected to manufactured the product, the dimensions of the product were the same.

## 7. Conclusion

This paper has proposed an approach that considers two key parameters (material selection and transportation) to predict the carbon consequences of early design decisions. DES models were built based on an engineering case study to understand the impacts of product architecture on engineering supply chain and a numerical equation was used to calculate the carbon emissions. There were assumptions made and system boundary, i.e., mass of product, material carbon coefficient, mode of transport, which was considered to predict carbon emissions which also aided in narrowing down the breadth of environmental sustainability in engineering supply chain. Carbon emissions arising from material selection decisions were calculated using the mass of the product (from CAD) and a carbon coefficient (from a materials database). These were incorporated in supply chain simulation models that also included carbon emissions related to the transportation of products from suppliers to customers. Alternative supply chain structures reflected early design decisions on a product's architecture [23]. It can be seen from Fig. 4 that, while there is variation in carbon consequences of material selection decisions, different supply chain structures, which mirror the product architecture, had a higher impact. Further, from Fig. 5, there in associating carbon emissions with individual products, it is important to consider fixed costs that can be amortised in different ways. Due to multiple aspects of sustainability, there are trade-offs that need to be considered. For example, manufacturing a product by using additive manufacturing (AM) helps in minimising material waste, however the energy generated for production and its cost is higher than traditional manufacturing.

As with any model, there is room for improvement in the simulation models developed as a part of this research. First, it was assumed that all products were manufactured in a single country because variations in electricity grid GHG emissions were not considered. In practice, this is unlikely to be the case and factoring in locations of manufacture will affect the processing energy and carbon footprint. From the case study, all the parts are transported using a lorry which has different carbon emission coefficient comparing to other modes of transport. In the future, global manufacturers and suppliers can be included in such models, which is likely to create a need to include different modes of transport. Further, the complexity of the case study was very low in that there were a small number of parts and all were made from one of five materials. In the future, more material options could be included and different parts could be made from different materials given the variety of materials commonly used in engineering. Although the underlying principles used are unlikely to change, working with more complex products (e.g., with more parts and where different material selection options apply to different parts) will add complexity to the simulation models and so the interfaces (in our case implemented using Microsoft Excel) that design teams use to generate to models and visualise the results.

This paper introduced an approach that can be used to predict carbon consequences of decisions made early in the design process, often well before any supply chain planning has begun, on the sustainability of manufacturing supply chains. Key findings driving future work lie in the importance of supply chain structure on carbon emissions and, in this context, the selection of appropriate system boundaries. Further two aspects of the supply network system boundary need to be considered: (1) the extent of the system, e.g., the supply network, under consideration and (2) the level of detail included and its coverage, e.g., $CO_{2e}$ is just one aspect of the UN SDGs. With respect to the extent of the system under consideration, we anticipate a need for suitably validated data (e.g., akin to material certification in manufacturing industries) in formats that can be integrated into models such as those introduced in this paper. In selecting appropriate levels of detail, key factors include the availability of data and the task for which it is being used. For example, when comparing design alternatives, factors that are common to all options may omitted but there is also a need for sensitivity analyses so that the most critical parameters are selected

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