12th International Conference on Through-life Engineering Services – TESConf2024
6-7 June 2024, Cranfield UK
DOI:10.57996/cran.ceres-2624

Integrating models for calculating component sustainability metrics

Leigh Kirkwood[a]*, Anees Abu-Monshar[a], Beth Norman[a], Robert Crook[a], Ed Barlow[b], Cai Hayes[c], Justyna Rybicka[a]

[a] *The Manufacturing Technology Centre, Coventry, CV79JU, UK*
[b] *Photocentric Ltd, Photocentric Ltd, Titan House, 20 Titan Drive, Peterborough, PE1 5XN, UK*
[c] *Essentra PLC, Langford Locks, Kidlington, Oxford, OX5 1HX, UK*

* Corresponding author. *E-mail address:* leigh.kirkwood@the-mtc.org

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Abstract

This paper reports on the development of models for calculating sustainability metrics at a per part level, developed for the LEAD factory project. While many organisations collect site level data for sustainability, there is a notable lack of support to calculate at a per part level. This scope difference requires different methods, but part level information can aid organisations in making production changes to achieve sustainability KPI's. A cradle-to-gate approach was used that links raw-material, the transportation of materials and details on the production processes. To achieve this, a toolset of different models was designed and built to address key activities in the value-chain, to both support potentially independent analysis of just that value-chain link or the more complete cradle-to-gate analysis. Integration of model outputs and planning of information flow within the toolset is the primary focus of this paper.

This is part 1 of a 2 part paper: this paper focuses on how the models were integrated and the design of the wider toolset. Part 2 focuses on the benchmarking using the model-set and comparing the "JENI" system developed as part of the LEAD factory project.

Keywords: Sustainable manufacturing; supply chain; carbon-dioxide equivalent

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1. Introduction

The challenge of de-carbonising our economy will require significant changes to how societies goals are met. Within manufacturing the challenge introduces a need to analyse entire value-chains to identify potential intervention strategies to reduce carbon emissions. Many organisations are currently making efforts to get sustainability information for the sites at which they operate. While this site-level analysis will be of use for strategic decisions, it does not aid in the many tactical interventions that could be possible. One of the more dramatic operational changes available to manufacturing would be the changing the process.

Industry is also increasingly interested in the energy being embodied within a product; partially due to the environmental impact of generating energy and partially because of the cost of energy. Recent energy price volatility has meant that the role of energy as a cost-driver has been more obvious.

The LEAD project is exploring the opportunity to change Plastic Injection Moulding (PIM) to a more carbon and energy efficient Additive Manufacturing (AM) process [1]. To support this project the Manufacturing Technology Centre (MTC) has developed models to support analysis of a product journey from raw materials until competition of production, (so called "cradle-to-gate" analysis).

The development of models for a per-part scale of analysis gives the opportunity, when combined with data from digital manufacturing systems controlling and monitoring production, to give very specific embodied carbon and energy figures for a particular produced part and not just the average for parts of that type, (i.e. if the grid power mix is particularly low carbon during a sunny/windy time parts made during that time would be lower carbon than typical). This allows accurate and transparent allocation of carbon emissions associated with product manufacturing.

2. Background

Though existing commercial models are available for predicting carbon emissions, (such as SimaPro [2]), there is a need for developing a set of models that would complement the existing capability for cost modelling [3]. The work of Rybicka et al. [3] is previous work established the methodology for building models that was followed during this work. Developing the ability to model carbon and embodied energy alongside the assessment of the financial cost of a process gives a great insight into the processes used and products generated, allowing efficiencies to be found, particularly for energy consumption.

The industry requirement for clearer information on emissions associated with commercial activities is becoming increasingly important. For instance, the introduction of stricter EU rules regarding emissions through the Carbon Border Adjustment Mechanism (CBAM) will lead for further need to understand emissions generation at different steps of the product value chain. The CBAM currently covers Emission-Intensive and Trade Exposed (EITE) industries [4]. EITE particularly addresses products such as cement, iron, steel, aluminium, fertilisers, and electricity [4]. The CBAM is designed to help reduce emissions through charging imports to the EU of those highlighted goods, to bring parity to products produced internally to the EU which require carbon certificates to be bought. While PIM products currently are not on the list of EITE products, changes to the rules could be considered a risk for any UK manufacturing industry that exports to the EU, and adds another motivation to explore carbon-efficient technologies. Potential introduction of similar rules within the UK market (to achieve carbon-neutrality by 2050) or other important markets should also be considered.

3. Toolset design- integration of models

One of the clear challenges of creating this toolset of models was integration of these models so that the cradle-to-gate analysis could be completed.

MTC internal guidance on building a model outlined a development process, but getting models to interact within a toolset added more complexities.

The toolset development started with a process of requirements capture to ensure that the toolset was able to deliver the required analysis. The capture process involved discussion with subject-matter experts and industry consortium partners and aimed to present and collate the high-level requirements.

Before individual models were designed, the scope of each model was carefully mapped against stages of the value-stream map. This resulted in splitting the challenge into complimentary model scopes:

- Raw materials
- Inbound Transport
- Processing
- Packaging
- Outbound Transport
- Overhead

The above models were also mapped so that interactions between them could be planned and data types and formats agreed.

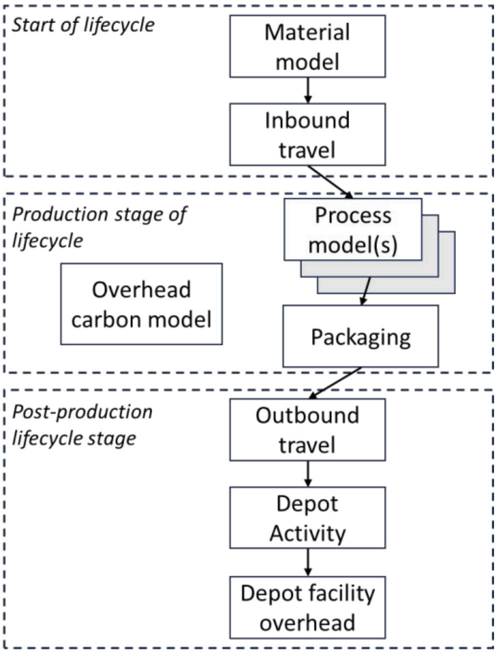

Fig. 1. Initial model map.

The model-map in Figure 1 was a strong starting point but as development moved forward it was clear that some refinement was needed.

3.1. Toolset Refinements

For the materials model multiple separate iterations of the model were needed to avoid material results being combined together and give misleading results. Separation also allowed users to keep model outputs clearly delineated; *i.e.* the results for materials associated with processing could be separated from materials contribution to packaging of materials. The material model iterations were functionally identical, raising the possibility for coding the materials model as a class and using multiple instances of that model.

AM and PIM were initially considered to require specialised models to capture the complexities of their operation. This quickly got revised as though the actions for both processes were differently labelled, this was the extent of the differences. The process model could be generic model; indeed the process would not have to be manufacturing specific- maintenance processes could just as appropriately be considered and assessed.

The packaging model was divided, into packaging model (focused on the material and energy consumption embodied into part packaging) and unpacking model (focused on the unpacking activity associated with goods into the production facility). Both models calculate outputs at a per part level. For the packaging model, parts being combined into a “package” was considered. Therefore, the model calculates “package” level sustainability impacts and then assigns a proportion to each part manufactured. The unpackaging model was focused on establishing the contribution of packaging coming into a production facility, and correctly attributing this to a part level. This was somewhat complicated by materials being consumed for a part being greater than the sum-weight of that part, due to scrap related material losses. Therefore, an additional step was required where the number of parts made from a given shipment of raw material needed to be modelled, using information generated from the process model. The unpacking models’ dependency upon a different model within the toolset made the two packaging activities sufficiently different that two models were needed.

Very early into the toolset mapping, the inbound and outbound transportation models were consolidated into a single model. It was found that the inputs were the same as were outputs. For practicality we found two iterations of the same model helped to separate the inbound and outbound results; which is helpful when assigning transport results to different organisations or to scope 1 or scope 3 emissions.

Initial plans for models addressing production overhead, depot activity and depot overhead were also consolidated into a single model. There was generally less complexity in this area than anticipated as production and storage were often in the same location. Should a more complex scenario arise where multiple locations are being used for storage or production, then the single overhead model developed can be used in multiple iterations; similar to the way transport model is used.

3.2. Final toolset model map

With the structural adjustments and simplifications completed within the previous subsection, the final toolset outline was generated.

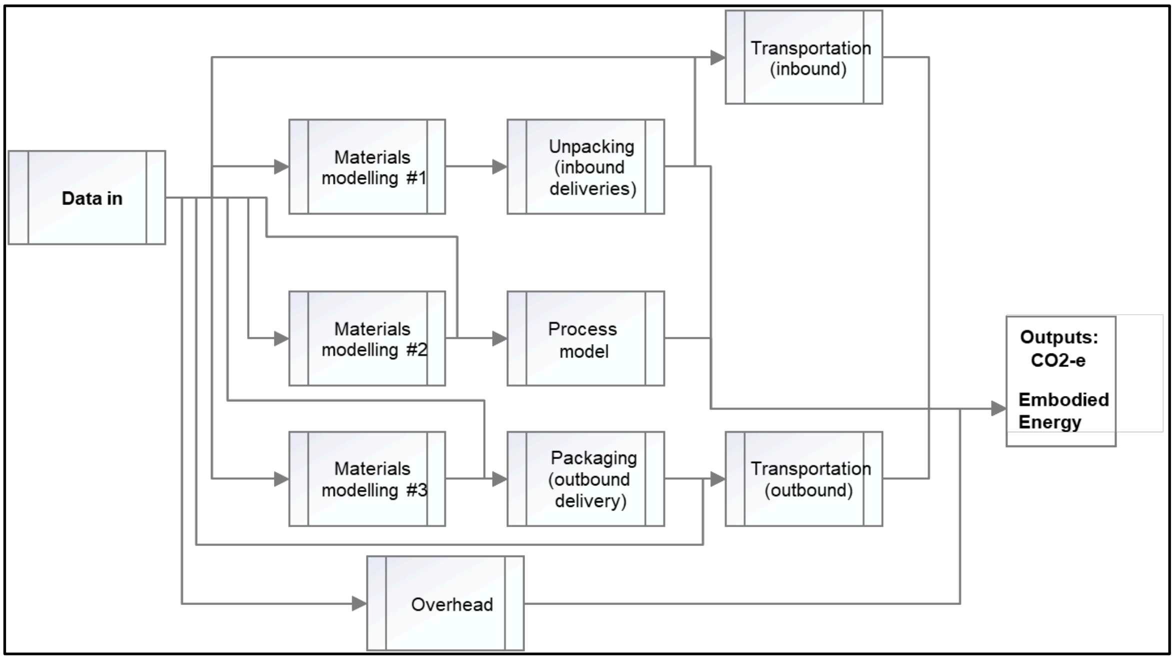

Fig. 2. Final toolset model map.

The final toolset model map is shown in Figure 2, outlining the three iterations of material model used and the two iterations of transportation model. The two packaging types of models are also present. This structure formed the basis of modelling efforts within the LEAD project at the MTC, the benchmarking results are presented in the second paper presented at this conference.

3.3. Data availability and structures

Data inputs to models were defined at a high-level and refined as development went on, but early planning of the interactions between models helped avoid costly re-engineering of models and gave developers a chance to benchmark against other model designs within the toolset.

We took inspiration from IDEF0 methodology and recorded all inputs and outputs expected for each model within the toolset, and captured these as images. These high-level diagrams containing defined outputs could be checked against requirements, and gave good starting points for developing designs of the model. An example IDEF0-inspired image for a model developed within the toolset (the materials model) is shown in Figure 3.

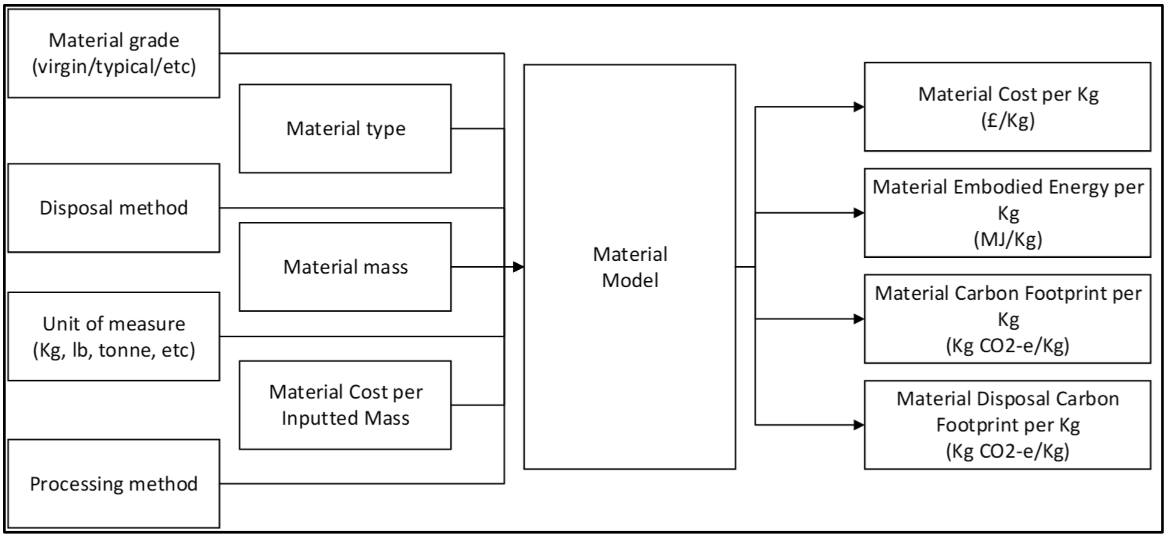

Fig. 3. IDEF0-inspired schema of material model.

The IDEF0-inspired method helped to preserve a high-level view of the toolset and to map interactions. The mapping of model inputs and outputs identified instances of models earlier within the information flow failing to supply information to later models. The materials model shown in Figure 3 outlines that disposal method was a data requirement. We use this to calculate the material disposal carbon, using the data available from the UK government [5]. This helped to calculate the impact of process scrap or other material burden inefficiencies. This can also capture information outside the cradle-to-gate analysis and give information on the end of the product lifecycle, if that lifecycle stage be introduced to the scope of analysis.

Once the toolset has been used to generate data for carbon-dioxide equivalent & embodied energy, there is the complication of breaking the total carbon down into the three emission scopes, (as defined by DEFRA guidance [6]).

- Scope 1 Direct emissions
- Scope 2 Energy indirect
- Scope 3 Other indirect

This approach gave the total carbon dioxide equivalent embodied within a product, the breakdown across scopes of the emissions and details on where along the value-stream emissions were embodied.

4. Modelling results

To demonstrate the use of the toolset a mass-produced item was selected, and analysed using information on PIM and AM processes. A printed circuit board (PCB) spacer is ideal as it is made in large numbers and is widely used around the world.

We defined a single PCB spacer as the unit of interest for the analysis. The analysis will be cradle-to-gate, this is a well-known scoping term; meaning that the embodied emissions of raw-material production, associated transportation, and manufacturing are considered. Outbound transport data includes moving to storage, our “gate” in the analysis.

This scope definition excludes product delivery to client, in-service, and disposal stages of a typical product lifecycle; all stages for a cradle-to-grave type of analysis. We use cradle-to-gate to focus more on the production and the impact of a potential change to an AM method.

Essentra was able to supply details on their manufacturing process, while Photocentric were able to detail their photoresist AM process. The AM process includes several distinct steps: printing, washing, rinsing, and curing, each utilising specific power ratings. A single print can produce multiple parts simultaneously, contributing to the efficiency of the process. Materials information was gathered from Granta Selector [7], with transport data being supported by data published by the UK government [5].

Table 1. PIM and AM Comparison of Carbon Footprint per Part

Stage	PIM	AM	%
Inbound Transport	0.182	NA	-
Unpacking	0.032	NA	-
Process Energy	0.743	0.132	-82.28%
Process Materials	7.819	1.158	-85.19%
Part Packaging Material	0.001	0.001	0.00%
Outbound Transport	0.032	0.032	0.00%
Total	8.595	1.322	-84.41%

Results of modelling the PCB using PIM and AM are shown in Table 1. Our results indicate an expected reduction in embodied carbon-dioxide equivalent of 84.41%. It should be noted that this figure for AM production does not include some contributions of the packaging required for the raw material and transportation of materials into the process; because of difficulties in determining supply chain details for that scenario. Their contributions are not likely to be significant. The details used in this comparison scenario are being reviewed as part of our verification & validation process and are likely to be revised in later publications.

5. Discussion

By writing this paper the authors have tried to show the approach used and guide any future model development by external teams.

When there are viable commercial models for sustainability available, the need for a separate model is perhaps unclear. Compared to many commercial offerings the advantage of this toolset is the flexibility of the modular design. This allows adjustment of the toolset to easily address challenges related to manufacturing. That the model is industry agnostic by design helps to ensure flexibility across industry-sectors.

While the focus of the particular project has been comparison between PIM (Plastic Injection Moulding) and AM (Additive Manufacturing), there was an understanding that such an approach can be used for any manufacturing process; largely as a result of generic model inputs. We have also noticed that many other challenges can be addressed using this toolset; for example, with some readjustment of the system-boundaries we can analyse the impact of supply-chain changes. This will be useful for any reshoring analysis that might be of interest. A further area that could be of interest is maintenance. Maintenance is notorious as having a lot of complexity, but if looking at a relatively small scope of problem, such as a single intervention, we believe that the process model can be used satisfactorily. This flexibility across manufacturing was intended, but the potential applicability beyond the manufacturing processes was an unexpected feature of this toolset.

Commercial partners within the consortium are implementing carbon-accounting functionality into their machines. The model is flexible enough to use continuously updated values of grid carbon dioxide equivalent intensity from external Application Programming Interfaces (API's), for example the UK's National Grid ESO [8]. This live data-feed enables monitoring of the exact carbon-dioxide embodied within a product, and with suitable digital manufacturing monitoring and data tracking, two products of the same type can be known to have different embodied carbon-dioxide equivalent, even if the same energy is embodied.

6. Conclusions

This paper seeks to provide an overview of the work done to integrate a series of models created to assess the carbon dioxide equivalent emissions and energy embodied within a product. While we have used a possible conversion from injection moulding process to an additive manufacturing process, the toolset was intended from its inception to be generic of process. The focus of this paper is on sustainable manufacturing but within the TES context, the toolset could be focused on maintenance activity and supply chain assessment. The generic nature of the toolset introduced some challenges during design and development but give significant flexibility to tackle any manufacturing process (and likely any maintenance or re-engineering process too). This paper is part 1 of a 2 part set of papers. This paper focused on the integration and design challenges, while paper 2 focuses on the benchmarking and testing of the toolset. Together they give a very clear guide on how the toolset was developed and how capable it is.

Acknowledgements

This work has been carried out as a part of the LEAD Project 2022-2024 funded by Innovate UK and was developed in collaboration with MTC (Manufacturing Technology Centre), Photocentric Ltd, Essentra PLC, Unipart Ltd, and Games Workshop PLC.

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