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Detection of Cause-Effect Relationships in Life Cycle Sustainability Assessment Based on an Engineering Graph

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Abstract

Although Life Cycle Sustainability Assessments (LCSA) are important in evaluating the sustainability of complex products and services, there is no sufficient support for engineers performing LCSA. The concept of an Engineering Graph focuses on the relations of data within engineering. It provides a model that leverages existing data in engineering and extendibility to include specialized databases and open and public data from the semantic web. This paper proposes a concept of how Engineering Graphs can be used to address the issues of LCSA and support engineers.

Keywords: model-based systems engineering (MBSE), life cycle assessment (LCA), artificial intelligence (AI), life cycle sustainability assessment (LCSA), engineering graph

1. Introduction

Sustainable development and consequently the establishment of a circular economy may be some of the biggest challenges facing humanity in the coming decades. In the context of the ongoing digital revolution, digitalization, networking and artificial intelligence (AI) can be drivers to solve sustainability issues (Mondejar et al., 2021; Nakicenovic et al., 2019). This approach can also be transferred to the field of sustainable product development. More and more complex products with global supply chains, produced in high volumes, cause multiple impacts in the environmental, social, and economic pillars of sustainability over their complete life cycle. This great complexity makes it challenging to assess products holistically and comprehensively and thus even more challenging to optimize these products in a more sustainable direction. For example, Model-based Systems Engineering (MBSE) can be a tool to manage complexity over the whole product life cycle (Dumitrescu et al., 2021), which has led to its widespread use in product development.

On the other hand, with increasing digitalization and networking and the rapid development in the field of AI, new tools and technologies are being generated to solve highly complex and interconnected problems (Dumitrescu et al., 2021).

Consequently, this paper shows how the application of an Engineering Graph based on graph databases can model a complete life cycle and how, in a second step, improvements in sustainability can be achieved by applying an AI-based extension of this model.

After this introduction, the paper first gives an overview of the current state of the art in sustainable product development, MBSE, and Engineering Graph in section two. Section three proposes the concept of an Engineering Graph, followed by an exemplary application of the concept in a case study in section four. The discussion and outlook in section five summarize and conclude this paper.

2. State of the art

2.1. Life Cycle Sustainability Assessment

In 2015, the United Nations (UN) published its 17 Sustainable Development Goals as one of the efforts towards sustainable development, including Goal number 12, "Sustainable Consumption and Production" (UN General Assembly, 2021). Against this background, new concepts and approaches in the field of sustainable product development are constantly being proposed (Costa et al., 2019; St Flour and Bokhoree, 2021), which on the one hand, improve the analysis of products with their impacts and, on the other hand, support product engineers during the product development process with synthesis methods. One decisive factor is to consider the product life cycle as completely as possible (United Nations Environment Programme, 2004) and to consider all three pillars of sustainability. This can become a great challenge since products are becoming increasingly complex, as mentioned in the introduction. Among others, the United Nations Environment Programme's (UNEP) Life Cycle Initiative attempts this comprehensive, so-called "life cycle thinking" in various disciplines such as Life Cycle Management (LCM) (Remmen et al., 2007) or Life Cycle Sustainability Assessment (LCSA) (Finkbeiner et al., 2010).

Initially published by Kloepffer (2008), LCSA aims to consider all three pillars of sustainability. It is therefore composed of three existing assessment methods: Life Cycle Assessment (LCA) covering the environmental pillar (DIN EN ISO 14040, 2009), Social-Life Cycle Assessment (S-LCA) (Benoît et al., 2013), (Benoît et al., 2013; Benoît Norris et al., 2020) covering the social pillar and Life Cycle Costing (LCC) (Hunkeler and Rebitzer, 2003) covering the economic pillar. So LCSA can be defined as: LCSA= LCA + S-LCA + LCC (Costa et al., 2019; Kloepffer, 2008).

Although LCSA currently offers one of the most comprehensive ways to assess products, Valdivia et al. (2021) highlight, besides others, the following challenges*: "consider only two pillars, lack interconnectedness among three pillars, not follow cause-effect chains and mechanisms leading to an endpoint"*. In particular, the cause-effect chains pose a complex problem as they attempt to trace within the Life Cycle Impact Assessment (LCIA) (United Nations Environment Programme, 2016) which impacts of products have which multiple effects on the environment and society. Based on the Life Cycle Inventory data, the cause-effect chains are linked via midpoint impact categories to endpoint categories to estimate the effects of the products on the relevant areas of protection. In our global society with globally interconnected ecosystems, exploring these cause-effect relationships requires further research.

Furthermore, Costa et al. (2019) criticize the high effort and the subjective definition of system boundaries and stakeholders, from which it can be concluded that most models are incomplete. Due to these insufficient models, no comprehensive analysis and thus no validation of optimization opportunities are given. This leads to the need for more sophisticated modeling and human support through new models and technologies, (e.g., MBSE).

2.2. Model-based Systems Engineering and Sustainability

Product Modeling evolved from a document-based approach towards MBSE, which facilitates modeling and reuse of engineering information across the life cycle (Estefan, 2007). The System Modeling Language (SysML), invented by the Object Management Group (OMG) in cooperation with the International Council of Systems Engineering (INCOSE), is based on the language and formalism concepts of the Unified Modeling Language (UML) (Eigner, 2016; Korthals et al., 2020). SysML models describe systems through requirements, structure, and behavior in a very abstract way. The language and diagrams are formalized in a way that can not only be understood by machines, but also by human engineers (Korthals et al., 2020).

Product development is typically supported by an Information Technology (IT) toolchain, which includes many IT systems such as Computer-Aided Design (CAD), Product Lifecycle Management (PLM), Manufacturing Execution System (MES), and Enterprise Resource Planning (ERP). All of these can be sources of information needed for LCSA. Although the data sets from the different IT systems provide views of the same product, their structures and schemas differ.

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Previous research, e.g., Bougain and Gerhard (2017); Buchert et al. (2016), shows that the information provided by a SysML model can be helpful when performing LCSA. The SysML model contains links to material and CAD data, and both combined were used to calculate Green House Gas Potential (GHGP) and Cumulative Energy Demand (CED) (Bougain and Gerhard (2017)). The Manufacturing Process and worktime, extracted from the ERP system, are used to calculate the GHGP and CED impacts of the manufacturing phase. SysML behavior models are used to model the usage phase by estimating how often a use case is conducted during the product life cycle and taking its impact into account. A limitation the authors identify is the difficulty for companies to implement this tool as links between different data management systems are needed (Bougain and Gerhard (2017)).
A different approach proposed by Buchert et al. uses Property Driven Development to connect product properties with desired environmental effects during the early design phases (Buchert et al., 2016). They conclude that coupling of different IT systems and product models can be beneficial. Future challenges include increased complexity, a high number of functional requirements leading to uncertainties, and time spent for information search by engineers in early design phases (Buchert et al., 2016).
It can be concluded that SysML models can be beneficial for LCSA, but the integration of the different data sources and IT systems is not sufficient yet. Furthermore, data sources especially needed for LCSA such as the life cycle inventory (LCI) databases (e.g. LifeCycleInitiative.org (2022)) were not considered.
Other researchers have developed systems that integrate product data from different IT systems such as PLM, ERP, and Internet of Things (IoT) into storage for metadata (Bajaj et al., 2017; Eickhoff et al., 2020; Eiden et al., 2020). Their solution integrates product data from different IT systems within a company, but it does not include data from suppliers and other external sources. Therefore, this paper proposes an Engineering Graph that focuses on the relationships of the data of different IT systems and databases and an extension with external data sources such as semantic web sources e.g. Wikimedia, specialized databases e.g. LCI database and public sources e.g. tender documents.

2.3. Engineering Graph

Bitzer et al. (2017) introduce the evolution of product modeling from MBSE (via SysML) towards Engineering Intelligence (via graph databases or semantic networks). This paper introduces the Engineering Graph, based on graph database technology, to propose an implementation of the high level of digitalization in engineering that supports the usage of AI (Schweitzer et al., 2020).
A graph database focuses on relationships between data points. It consists of nodes that represent entities and lines that represent the relationships between these nodes. Each node can have properties that can be used to filter and find data quickly (Rawat and Kashyap, 2017). These properties can be qualitative or quantitative information. Objects and their relations are represented naturally and clearly by using abstraction concepts (Angles and Gutierrez, 2005). Contrary to relational databases, the schema is not fixed when creating the database, allowing the integration of different schemas (Angles and Gutierrez, 2008). Therefore, data from different sources can be integrated without the need to match the schemas first, which allows the graph extension with new and not anticipated sources. This is especially useful in a complex environment such as engineering.
Graph databases are more efficient than traditional relational databases with datasets that contain many relationships (Vicknair et al., 2010). They might be considered when *"1. Having tables with lots of columns, each of which is only used by a few rows. 2. Having attribute tables. 3. Having lots of many-to-many relationships. 4. Having tree-like characteristics. 5. Requiring frequent schema changes."* (Vicknair et al., 2010).
By focusing on the connections between data points, the query language can find and analyse paths, neighbourhoods, and patterns in the data (Angles and Gutierrez, 2008). This can allow new insights into highly interconnected datasets.
An Engineering Graph is the application of graph databases in an engineering environment. It connects the data from SysML models, traditional engineering applications such as domain-specific systems, PLM and MES systems, company data from ERP systems, and field data from IoT systems. These systems all have their schema and logic, which limits interoperability and the ability of the systems to work with each other. The capability of graph databases to include data with different schemas is crucial and allows the creation of an Engineering Graph. The concept of an Engineering Graph is visualized in Figure 1.

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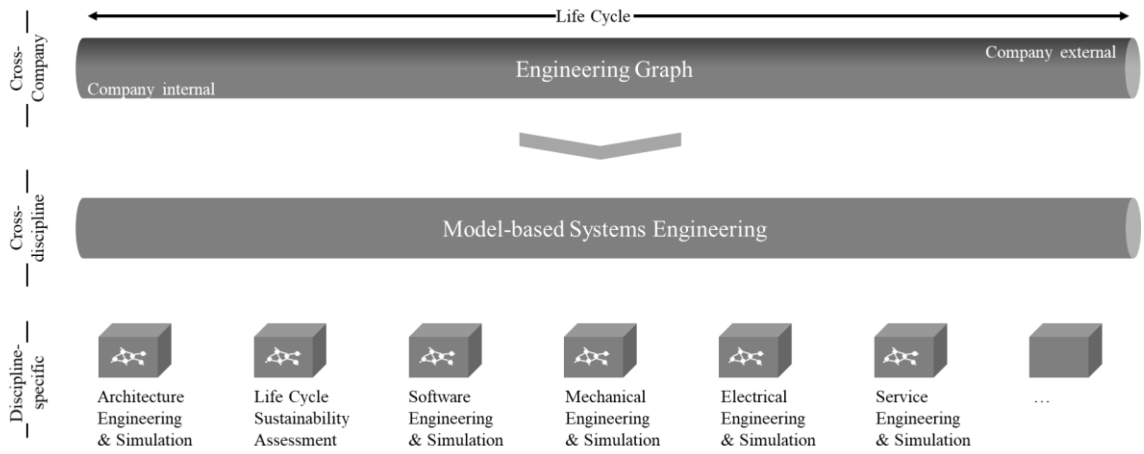

Figure 1. Engineering graph concept

Additionally, to the company internal data, the Engineering Graph can contain data from different suppliers or partners. It is designed in an open and extendable way that allows sharing and connection of data across company borders.

The Engineering Graph can also contain information from public sources such as from the semantic web or from specialized databases such as the various LCI databases (LifeCycleInitiative.org, 2022) which contains information about the ecological impact or the social circumstances.

The Engineering Graph is useful in all applications that span the product life cycle. The following section will propose a method of how an Engineering Graph can support LCSA.

3. Engineering Graph supporting LCSA

As stated in sections 1 and 2, the main issues with the current LCSA are the increased product complexity with more globalized supply chains, both result in many related and interconnected cause-effect chains leading to an endpoint. These relations and mechanisms are currently only partially included in models supporting engineers in performing LCSA. Additionally, the extendibility of these models with new data is a manual and slow process.

In order to address the issues stated above, engineers would benefit from a system that (a) connects data from different sources, (b) focuses on the connection of data points, (c) has the flexibility to include more sources with unknown structure and (d) allows exploration of the extended system. This paper proposes that an Engineering Graph as described in section 2.3 is well suited to provide this functionality and therefore can support engineering in performing LCSA.

The Engineering Graph needs to contain the connections of data across the different systems of interest. The system of interest can be a specific part of a product, the product itself, or the product including all related services. Depending on the system of interest, several databases such as PLM, MES, ERP, IoT, or Customer Relationship Management need to be included. This means, that existing models, e.g. MBSE models, are leveraged to create the Engineering Graph. Information from suppliers of parts or raw materials regarding their sourcing and production process and logistics are needed. The goal is not to duplicate all information from different databases in the Engineering Graph but to focus on high-level points and the relationships of the data.

After connecting all company internal data and including data from suppliers, the Engineering Graph can be enriched by open data sources such as Wikimedia (Wikimedia, 2021) and the google knowledge graph (Google, 2021). Both sources are part of the semantic web and already contain large amount of connected data that can be added to the graph. Therefore, a high-level point such as "dialysis machine" that was added to the Engineering Graph as a node from the MBSE model can be merged to the node "dialysis machine" that can be found in the Wikimedia data. This allows to extend the Engineering Graph with further data from Wikimedia.

In order to support the use case of performing LCSA, specialized data, e.g., from the LCI databases that is necessary for LCSA, can be added as well over the Application Programming Interfaces (APIs) of the specific LCI database.

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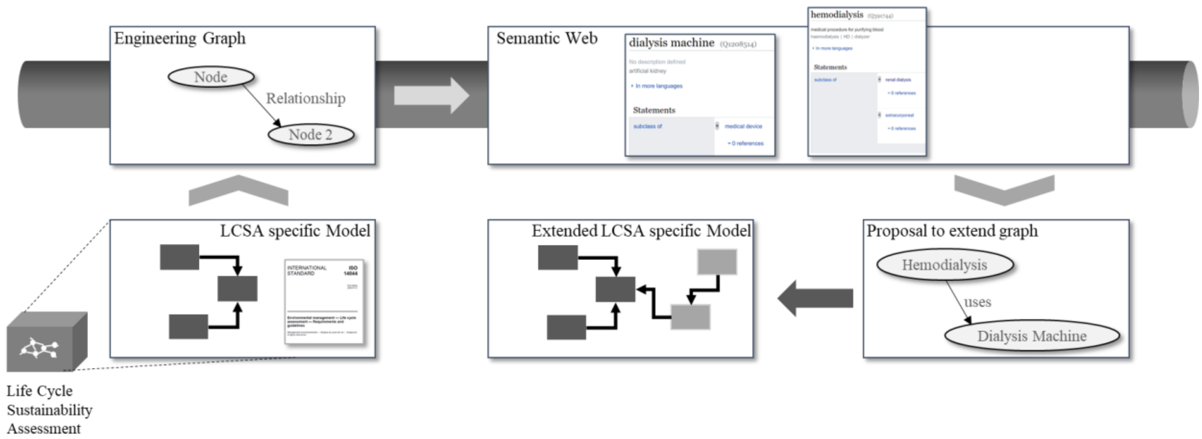

Figure 2. Engineering graph supporting LCSA

Figure 2 shows a schematic view of how the Engineering Graph can support engineers that are performing LCSA. In the initial LCSA-specific model, there exist already some cause-effect chains, since e.g., LCA tries to assign certain results from the LCI to different impacts on the environment. During this LCIA, different levels of detail can be achieved, such as midpoint or endpoint level (Bare et al., 2012). When these cause-effect-chains are transformed in a graph format and added to the Engineering Graph, the new nodes can be compared to existing ones. Additionally, the semantic web can be searched for related terms to enrich the Engineering Graph with public knowledge by extracting new or similar nodes using Natural Language Processing (NLP). The now enriched Graph can be analyzed to find new connections and cause-effect relationships, which are proposed to the engineers performing the LCSA and can be manually added to the LCSA specific model.
The following section will provide an example of how an Engineering Graph was created and used to support LCSA.

4. Use Case: LCSA for Medical Device

The Engineering Graph is created to support engineers performing LCSA at a leading manufacturer of medical devices. To initialize the Graph, a basic structure is created, as shown in Figure 3. It contains one node, "References", that connects to the norms relevant to the development of medical devices and the ones relevant for LCSA. From the "References", a node with "Requirements" is added. It can be connected to the requirements that can be derived from the norms. This node is connected to the "Outcomes" that fulfil the requirements, and the "Outcomes" are connected to the "Process" where they are created. The process can be the product development process which creates the products and services as outcomes, or the LCSA process, which creates the LCSA document as the outcome. The product structure information of a company's products can be imported from an existing SysML model.

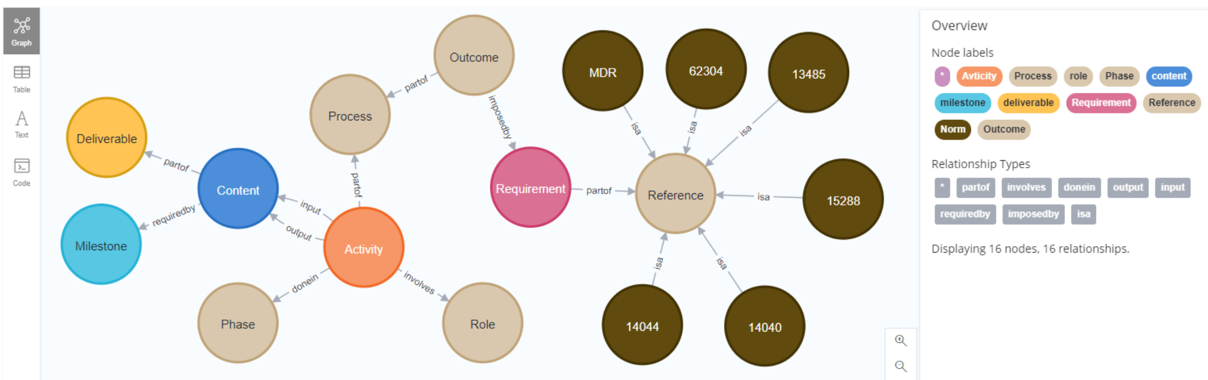

Figure 3. Basic structure of engineering graph

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After the company's internal data is part of the Engineering Graph, it can be extended to include LCSA specific data such as several midpoints and endpoints, as shown in Figure 4. These are also linked to each other and can be used when linking Life Cycle Impact Factors such as CO2 emissions to the "Climate Change" midpoint that is already linked to "Resources", "Ecosystem Health" and "Human Health". These connections can be reused for each LCSA for every product. The Engineering Graph can be extended by new midpoints, endpoints, or relationships when researched and published.

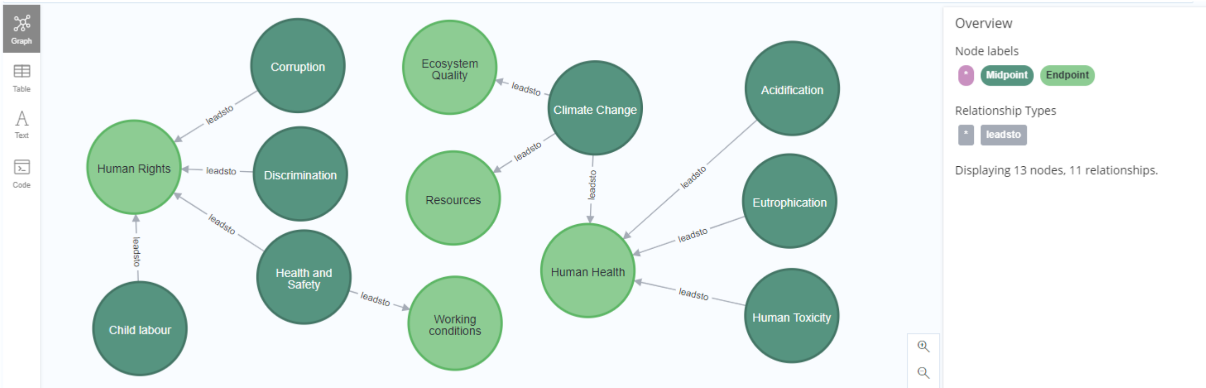

Figure 4. Graph containing LCSA data

Further sources relevant to the specific use case of LCSA or the medical device industry, such as the World Health Organization (WHO), can be added. Figure 5 shows the "Health System Building Blocks" according to the WHO (World Health Organization, 2021) and how they are connected to existing data. The node "Role", which is part of the basic structure of the Engineering Graph, is also part of the "Health Workforce", and the "Outcome", representing the company's products and services, is part of the "Medical Products, Vaccines and Technology". With these connections, all information published by the WHO regarding the Health System Building Blocks can be added and linked to provide further context to engineers performing LCSA or during product development.

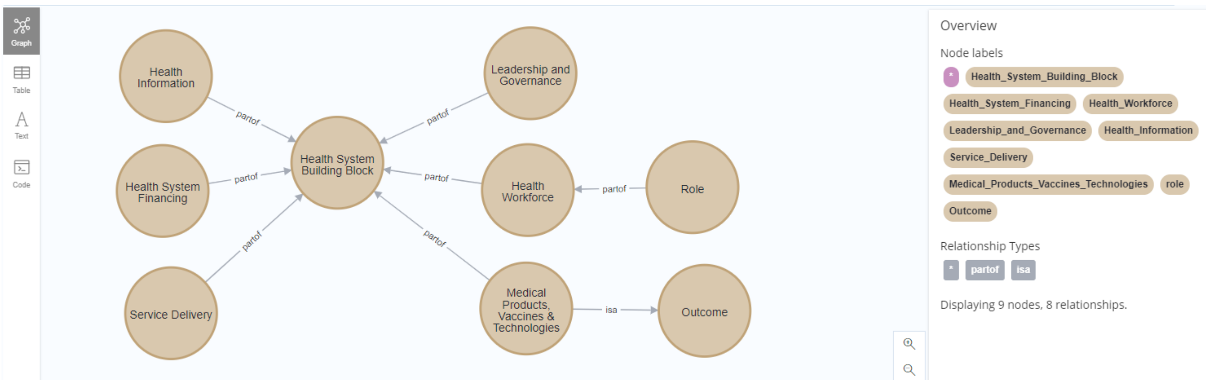

Figure 5. Engineering graph containing WHO data

The Engineering Graph with the LCSA relevant data can be analysed with data science technology. Parts of the graph can be visualized so engineers can explore neighbouring nodes and discover new possible cause-effect relationships. These can be detected by leveraging a more integrated view on previously neglected parts of the life cycle, allowing a more holistic view of the product and can support the assessment of its life cycle sustainability.

Detecting social impacts, where complexity is very high, and societies differ from country to country, benefits from integrating semantic web sources. These can be, e.g. changing labour laws, socioeconomic conditions, or education.

Quantitative insights such as the greatest polluters require that the nodes of the graph are extended by quantitative properties. That way, the Engineering Graph can support the identification of the greatest

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polluters in the life cycle and to address them to bring down the ecological footprint quickly and efficiently. For every product, the measures with the most significant impact to improve sustainability can be identified and executed. Additionally, interdependencies between the pillars of sustainability can be identified and considered. Even if the interdependency is hidden behind several corners, an Engineering Graph can find the quickest path between the pillars. Otherwise, hidden interdependencies and correlations can be made explicit in this way.

Another possibility is the discovery of alternative materials for medical applications. These materials could improve the ecological footprint of the products without sacrificing medical applicability. The Engineering Graph could show materials used in similar use cases, and engineers could decide on the applicability.

5. Discussion & Outlook

This paper introduces the concept of an Engineering Graph and indicates its usefulness for engineers performing LCSA. Therefore, current issues with LCSA are described, and a concept of an Engineering Graph is outlined. This concept is then used to support engineers performing LCSA in the medical device industry. It could be demonstrated that the focus on the relations of data and the extendibility of the Engineering Graph is well suited to support engineers performing LCSA in some of the mentioned issues. The usefulness of the Engineering Graph depends on the quality of the information that it contains. As existing models, e.g. SysML models, are used to create the Engineering Graph, their quality determines the quality of information that the Engineering Graph contains. This can lead to increased effort in creating a useful Engineering Graph when the models already existing need to be revised.

A limitation of the study presented here is that the prototype to validate the concept is at an early stage. Currently, the extension of the Engineering Graph prototype is a manual process. Further research is needed to (partially) automate the extension, especially when accessing open and public sources such as the semantic web.

Future research is needed to develop the current prototype further and demonstrate its usefulness when performing LCSA for a simple and more complex product. The user interface needs to be designed and tested. It is currently not decided how the users will interact with the Engineering Graph and the process of maintaining it needs to be developed and tested. Additionally, the Engineering Graph needs to be applied to use cases going beyond LCSA.

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