ENGINEERING GRAPH AS AN APPROACH TO SUPPORT DESIGN DECISIONS IN PRODUCT DEVELOPMENT

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ABSTRACT

The requirements space is increasing due to non-functional areas such as security, resilience and sustainability gaining in importance. This creates a complex and dynamic space which makes it hard for engineers to take good data driven design decisions. Increasing the quality of design decisions allows to better set up development projects and develop more successful products and services. The design can most heavily be influenced in the early design phases, where design flexibility is high and resource commitment is low. Unfortunately, the system knowledge is also low in early phases. The Engineering Graph is a concept that connects data from different internal and external sources. It allows to connect product data stored in Product Lifecycle Management systems with system models and also add external sources from the Wikimedia Knowledge Graph, World Health Organization and World Bank. This interconnected data allows the support of engineers in managing the complex and dynamic requirement space and provide high system knowledge in the early design phases to support design decisions.

Keywords: Product Lifecycle Management (PLM), Early design phases, Semantic data processing, Engineering Graph, Design Decisions

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1 INTRODUCTION

In today's world Security, Resilience and Sustainability are of increased importance (Wörner and Schmidt, 2022). The unprecedented times where disruptions of the supply chain, cyberattacks and even war are present move security and resilience into focus. On the other hand, decarbonisation and increased ecological awareness leads to a greater focus on sustainability. One way to achieve all three is the creation of innovations (Wörner and Schmidt, 2022).

When creating innovative products, engineers face a large requirements space from the different areas presented above. This space contains dynamic and potentially conflicting requirements. Taking near optimal design decisions is crucial but very difficult in this context. Design Decisions in the early design phases have a large impact on the final design. In early phases, design flexibility is high because no or only a few decisions have been taken. Therefore, resource commitment is low in the early phases and the design can be heavily influenced and chanced without high costs.

To take good decisions in the early phases, it is important to have high system knowledge. Usually, system knowledge is low during the early phases because no product data has been created. Increasing the system knowledge in the early phases can be vital in improving design decisions, as decisions can be based on data. Additionally, decision support systems can be established to support engineers in taking design decisions. As the product data cannot be available in the early phases because it will be created later, other information sources need to be explored and taken into consideration here. There are plenty of information sources freely available from public sources such as the Wikimedia Knowledge Graph, norms and regulations and information from non-government organizations (NGOs) such as the World Health Organization (WHO) or the World Bank.

This paper explores the Engineering Graph as an approach to make publicly available information that can support product development available in the early phases. Therefore, the state of the art of Lifecycle Engineering (LCE), Design Decisions and the Engineering Graph are presented in section 2, before the support of design decisions by the Engineering Graph is explored in section 3. Section 4 provides an exemplary use case from the medical device industry. The approach is discussed in section 5 and an outlook on future research is given.

2 STATE OF THE ART

In this section the state of the art relevant for this paper is introduced. First, LCE is introduced as a concept that spans the entire lifecycle of a product and focuses on several goals such as environmental, social and economic targets. Second, the importance of design decisions, especially in the early phases, and the types of decisions that need to be taken are introduced. After that, the Engineering Graph is explained as a concept that connects data from several sources and might prove useful in supporting design decisions.

2.1 Life cycle engineering

LCE is a sustainability-focused engineering methodology that considers the comprehensive technical, environmental, and economic impacts of decisions within the product life cycle (Hauschild et al., 2018). Therefore, the lifecycle needs to be defined.

In product development, the prevailing definition of the life cycle starts with product and program planning. The next phases are design and development, production planning, manufacturing (production, assembly, procurement), product distribution, product use and maintenance, and product recycling (Anderl, 1998; Eigner and Stelzer, 2013). This definition is strongly oriented towards the activities within a company that are necessary to bring a product to market, to operate it, and to remove it from the market.

LCE is the first engineering method that has the entire lifecycle as its scope. Prior methods as developed by Pahl and Beitz (Bender and Gericke, 2021), Product Lifecycle Management (PLM) (Eigner and Stelzer, 2013), Model-based Systems Engineering (MBSE) (Dumitrescu et al., 2021) and the VDI 2206 (Gausemeier and Moehringer, 2002) only have parts of the lifecycle in scope. Figure 1 shows which engineering methods focus on which parts of the lifecycle (Burr, 2008).

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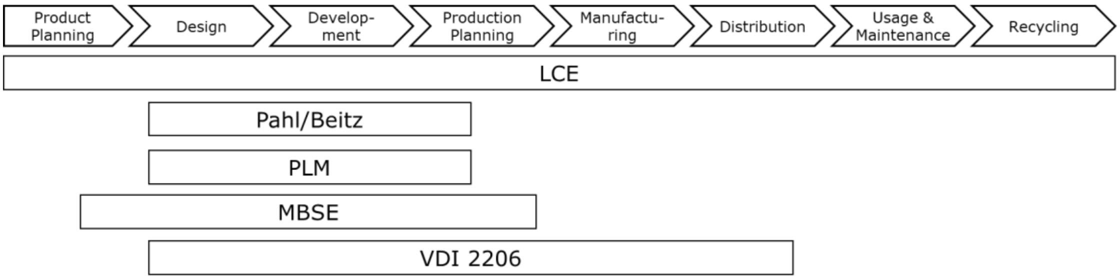

Figure 1. Engineering methods over the lifecycle based on (Burr, 2008)

As LCE focuses on the entire lifecycle, data from all stages of the lifecycle need to be considered. Currently there exists no LCE method that connects data from the entire life cycle and therefore makes it available in early phases. Table 1 summarizes the current issues with LCE that are discussed in the literature.

Table 1. Issues identified with current LCE (Schweitzer et al., 2023)

Issue #	Issue	Source
1	Lack of Speed	(Cerdas et al., 2018; Sakao et al., 2021)
2	Oversimplified models	(Cerdas et al., 2018)
3	Lack of comprehensiveness	(Cerdas et al., 2018)
4	Lack of transparency	(Cerdas et al., 2018)
5	Lack of integration between environments of core engineering disciplines	(Kaluza et al., 2018)

The broad scope of LCE means that a large amount of data is needed to support engineers in engaging in LCE. Currently, data from different stages of the lifecycle are managed in different tools and models that lack interconnection.

2.2 Design decisions

The decisions taken before and during product development are how the products and their development is shaped. This section introduces the state of the art of design decisions, how they influence products and product development during the lifecycle and how they can be classified.

Figure 2 shows the relationship of design flexibility, resource commitments and system knowledge. High design flexibility means that no decisions have been taken and engineers are free in designing the new product. Low resource commitments means that the resources budgeted for the development of a product are not spent and it can be defined by the design decisions where to spend them. The system knowledge usually builds over time during the development process as the system is being designed and marked feedback is gathered. Having a large amount of system knowledge early on can be a great benefit because here design flexibility is high so that the product can be designed better due to the higher system knowledge. Costs of changes are lower because the resource committed are low.

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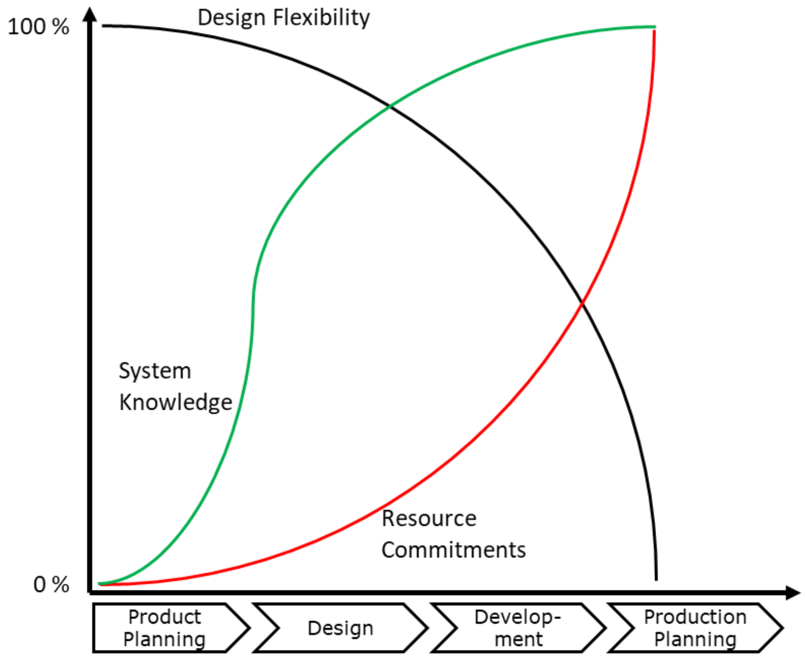

Figure 2. Relationship of system knowledge, design flexibility and resource commitments based on (Boy, 2019)

Prior research has shown that the impact possibility of management is highest in the early phases of product development (Bitzer et al., 2007). This is because only few design decision have already been taken and the high design flexibility can be used to influence the design.

Kaul and Rao (1995) classify design decisions into two types. First, decisions regarding the positioning of a product and second, decisions how this positioning can be put into action (Kaul and Rao, 1995). The first types of design decisions focus around the set up of a development project. Table 2 shows the typical decision types that need to be taken in that phase.

Table 2. Decisions in setting up a development project (Krishnan and Ulrich, 2001)

	Decision
Project Strategy and Planning	What is the market and product strategy to maximize probability of economic success?
	What portfolio of product opportunities will be pursued?
	What is the timing of product development projects?
	What, if any, assets (e.g., platforms) will be shared across which products?
	Which technologies will be employed in the product(s)?
Product Development Organization	Will a functional, project or matrix organization be used?
	How will the team be staffed?
	How will project performance be measured?
	What will be the physical arrangement and location of the team?
	What investments in infrastructure, tools and training will be made?
	What type of development process will be employed (e.g., stage-gate)?
Project Management	What is the priority of development objectives?
	What is the planned timing and sequence of development activities?
	What are the major project milestones and planned prototypes?
	What will be the communication mechanisms among team members?
	How will the project be monitored and controlled?

When the project is set up and staffed, the product development can start. Now, the second type of design decisions are addressed. Within the project, design decisions regarding the product need to be taken in different design phases. Table 3 gives an overview of these decisions.

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Table 3. Product development decisions within a project (Krishnan and Ulrich, 2001).

	Decisions
Concept Development	What are the target values of the product attributes, including price? What is the core product concept? What is the product architecture? What variants of the product will be offered? Which components will be shared across which variants of the product? What will be the overall physical form and industrial design of the product?
Supply Chain Design	Which components will be designed, and which will be selected? Who will design the components? Who will produce the components and assemble the product? What is the configuration of the physical supply chain, including the location of the decouple point? What type of process will be used to assemble the product? Who will develop and supply process technology and equipment?
Product Design	What are the values of the key design parameters? What is the configuration of the components and assembly precedence relations? What is the detailed design of the components, including material and process selection?
Performance Testing and Validation	What is the prototyping plan? What technologies should be used for prototyping?
Production Ramp-Up and Launch	What is the plan for market testing and launch? What is the plan for production ramp-up?

In summary, prior research on design decisions shows that the design can be influenced most heavily and with lowest costs in the early phases of the development process. To take good design decisions, a high system knowledge is needed. Any method that can provide high amounts of system knowledge in early design phases might help in increasing design decision quality.

2.3 Engineering Graph

The Engineering Graph is a concept that leverages graph databases to connect data from different systems and silos including publicly available information (Schweitzer et al., 2022). The concept was first introduced by Schweitzer et al. (2022) to provide an artificial intelligence (AI) ready knowledge base to support AI use cases in engineering. The need therefore was identified by analyzing the AI building blocks and finding the need for a knowledge base that connects all engineering objects and includes publicly available information to provide further context (Schweitzer et al., 2020, 2021).

Graph databases focus on the relationships between data points. They consist of nodes representing objects and lines representing relationships where both nodes and lines can have quantitative or qualitative properties (Rawat and Kashyap, 2017).

Multiple sources with different schemas can be added to the Engineering Graph because the schema does not have to be fixed at the creation of the graph (Angles and Gutierrez, 2008). The Engineering Graph is useful in situations where there are many relationships between data points (Vicknair et al., 2010). This is the case in engineering, as different systems, databases and models are used during the lifecycle (Zingel et al., 2022). The Engineering Graph is an efficient way to connect these and provide a common database of the whole system knowledge.

The Engineering Graph can not only contain the data from engineering within a company, but also from additional sources. These can be public information from the WHO, World Bank, specialized sustainability databases and the Wikimedia Knowledge Graph, or any industry or domain specific source that might prove useful. Therefore, the Engineering Graph is well suited to solve the issues presented in section 2.1 and 2.2, namely the connection of data from multiple sources and the provision of high system knowledge in the early design phases (Schweitzer et al., 2023).

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3 ENGINEERING GRAPH SUPPORTING DESIGN DECISIONS

In this section the Engineering Graph is introduced and its use as a source of information during the early design phases is explored. First, the creation of the Engineering Graph, then the extension of the Engineering Graph is explained before its support for design decisions in the early design phases is presented.

3.1 Building the Engineering Graph

The Engineering Graph spans the entire product lifecycle. In the early design phases, where little to no classical product knowledge is available, it provides the knowledge from external sources. Figure 3 shows how the Engineering Graph develops during the lifecycle.

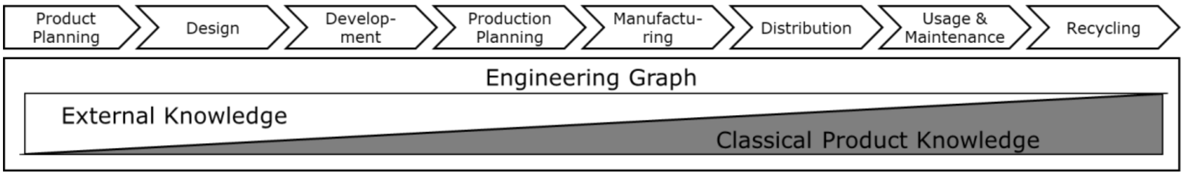

Figure 3. The Engineering Graph over the lifecycle

In the earliest phase, the Engineering Graph consists of only external knowledge. This knowledge comes from imports of the Wikimedia Knowledge Graph, Google Knowledge Graph, Norms and Regulations, and NGOs such as the World Bank or the WHO. The knowledge is preconnected to each other and can be used in the marked and strategy phase.

In the Design and Development phases, the classical product knowledge is created and stored in systems such as PLM, MBSE, Enterprise Resource Planning (ERP) and domain specific specialized engineering tools e. g. for simulation or testing. The knowledge created here can be connected to the external knowledge that is already part of the graph.

In the later phases, knowledge and field data from the use phase is added to the Engineering Graph. This can be connected to the data that is already in the graph.

In the next subsection the extension of the Engineering Graph is explored. New sources can and should be added during the lifecycle and existing information needs to be updated e. g. when a new version of a norm is released.

3.2 Extending the Engineering Graph

Extending the graph is needed to include new sources as they are published or discovered. Figure 4 shows the three steps necessary to extend the graph: identification of new nodes, identification of relationships and identification of the relationship type. The following paragraphs will describe the steps in more detail.

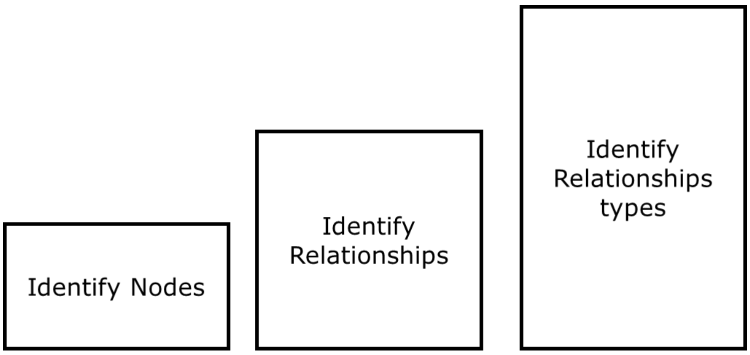

Figure 4. Steps to extend the Engineering Graph

Identify Nodes: The first step is the identification of new nodes that can be added to the graph. The new source can be added as one node, which is the easiest solution. An example would be that a new norm that should be added is represented by one node in the graph. This can be sufficient, but in some cases it needs to be broken down further. In this example, subsections of the norm can be added to the graph as separate nodes that are related to the main node. By that, it is possible to later relate an

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engineering object to a specific section of the norm. That allows more in-depth analyses later, e. g. when a norm is updated, and the update is only done in some of the sections of the norm. Having the subsections connected to engineering objects allows to automatically detect which engineering objects are affected by the update.

Identify Relationships: The second step is the identification of relationships. The goal is to connect the identified new nodes with existing ones. This can be done in several ways. The first way is manual, which requires high effort and deep domain knowledge to know how the new node is related to existing ones. The second option is based on keywords. This can be done by using natural language processing's keyword extraction capability (Beliga et al., 2015). After finding the keywords of the new source, the Engineering Graph can be searched for these keywords and relationships to the findings can be suggested. The third way is based on the current relationships of a node. The graph database can use machine learning to understand how the nodes are connected and suggest new relationships based on that.

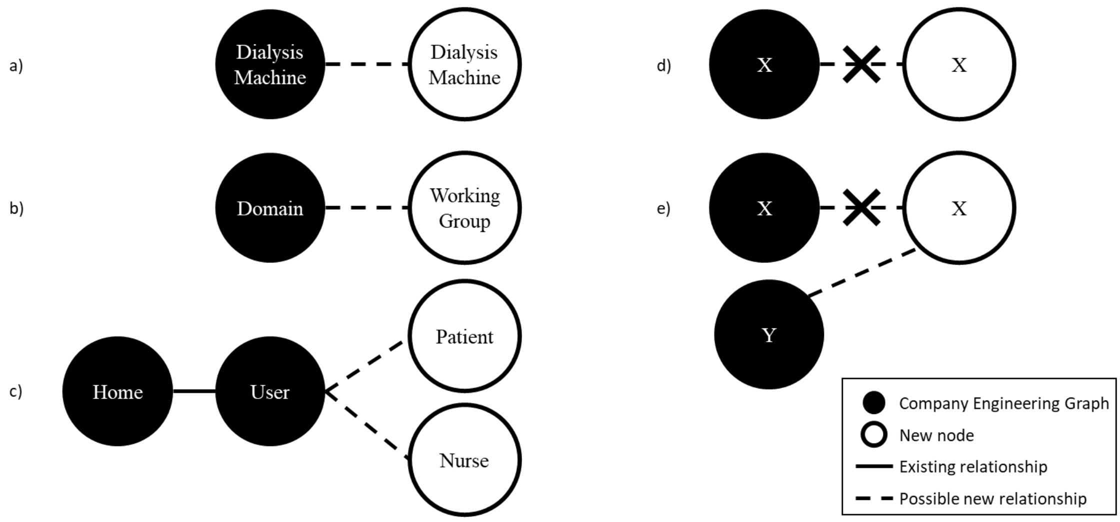

Figure 5. Identification of relationship types

Identify Relationship Type: The third step is the identification of the relationship type. Here, a case distinction is necessary as shown in Figure 5. In case a), the new node identified already exists in the Engineering Graph and can therefore be merged with the existing node. Both nodes have the same name and represent the same object. In case b), both nodes represent the same object, but they are called differently. In case c), the patient and the nurse could both be the user. A first level relationship needs to be considered additionally to provide the context which is correct. In this case, as the context is at home, the user is most likely the patient. In case d), both nodes have the same name but do not represent the same object. Here, no relation should be created. Case e) builds on that as there is another node in the existing Engineering Graph that represents the same object as the new node but is called differently. In all of the cases, after the relationship is clarified, the relationship can get a new property that specifies the relationship type.

It is important to note that the extension of the Engineering Graph can be supported by automation tools, but it is impossible to fully automate it with current technology. The system should only make suggestions that are then reviewed by human domain experts that verify and add the relations to the graph.

3.3 Supporting design decisions with the Engineering Graph

This section shows how the Engineering Graph can support design decisions. Therefore, first it is explored how the decisions needed when setting up a development project are supported and second, how decisions within a development project can be supported.

The Engineering Graph brings a rich database of connected information from multiple sources to the early design phases where design decisions have the highest impact. It increases system knowledge and connects that system knowledge with context information to support decision making in a complex and dynamic environment.

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The first class of decisions that the Engineering Graph supports is setting up a development project. First, decisions around project strategy and planning need to be taken. These can be supported by providing market information and connecting these with existing product information of other products and services that a company offers to support the detection of a valuable niche that a new product can fill. Second, the organization of the product development project needs to be set up. Here, the Engineering Graph can support by providing information on skills of employees and timelines of other development projects to plan when certain key employees are available. Third, decisions regarding project management are supported. The Engineering Graph can support here with setting the development priorities by providing the context knowledge needed.

The second class of decisions supported are during a development project. During concept development the Engineering Graph can connect the requirements with already developed parts from the company and therefore support in creating the product architecture and deciding which components can be shared across variants of the product. Connecting shipping routes and geopolitical information to the graph enables the support of supply chain design by providing data for risk analyses and make or buy decisions. Product design is directly supported by connecting requirements with material information and development and admission norms that allow enhanced material selection.

The increase of system knowledge by connecting system data with context information is useful during every design phase. Dynamic changes of context information can be reflected in the graph by extending and updating it which can support decision making and revising in real time.

4 ENGINEERING GRAPH IN THE MEDICAL DEVICE INDUSTRY

In this section two use cases from the medical device industry are presented. The first use case is bringing an already developed and approved medical device from one continent to another and approving it there with a new notified body. The second use case is the development of an entirely new medical device.

The first use case is an approved medical device that is currently being sold in Europe that should be brought to the market in the United States of America (USA). Therefore, the product needs to be approved by the Food and Drug Administration (FDA). The Engineering Graph can be of help here as the entire product data of the product is already part of the graph. Now, the information specific to the new market such as hospital locations, altitude, temperatures, air pressure, etc. can be added as well as the requirements for approval by the FDA. This information is linked to the existing product data so that analysis can be performed if design changes are necessary to fulfil the additional requirements. Supporting engineers in the impact analysis and making the design changes significantly reduces time to marked and improves product quality as managing the complexities of the new market is supported by the data.

The second use case is a new product development. Here, no prior product data exists. Therefore, information from the World Bank about markets, demographics and economic conditions are combined with information from the WHO about health insurance coverage in different countries. Combining that with requirement analysis from tender documents of clinics in different continents and approval requirements of notified bodies leads to a dataset that supports the decision which markets can and should be entered. Finding the right market and knowing the conditions in the country leads to the right strategy and setting up the right development project.

Figure 6 shows an exemplary excerpt from the Engineering Graph, highlighting how data from several external sources can be connected to the product data. The sustainable development goals published by the United Nations (UN General Assembly, 2021) are highlighted in green, Endpoints and Midpoints from a Life Cycle Sustainability Assessment (LCSA) (Bare et al., 2012) are connected to the goal of "climate action" and demonstrated in red and orange. The Health System Building Blocks that were published by the WHO (World Health Organization, 2021) are linked to the Endpoint "human health" and the companies Product Family is connected to the Medical Devices Building Block. By this chain, information from the UN, LCSA and the WHO is connected with each other and directly related to the product data. This allows humans and machines to understand the product in its wider context.

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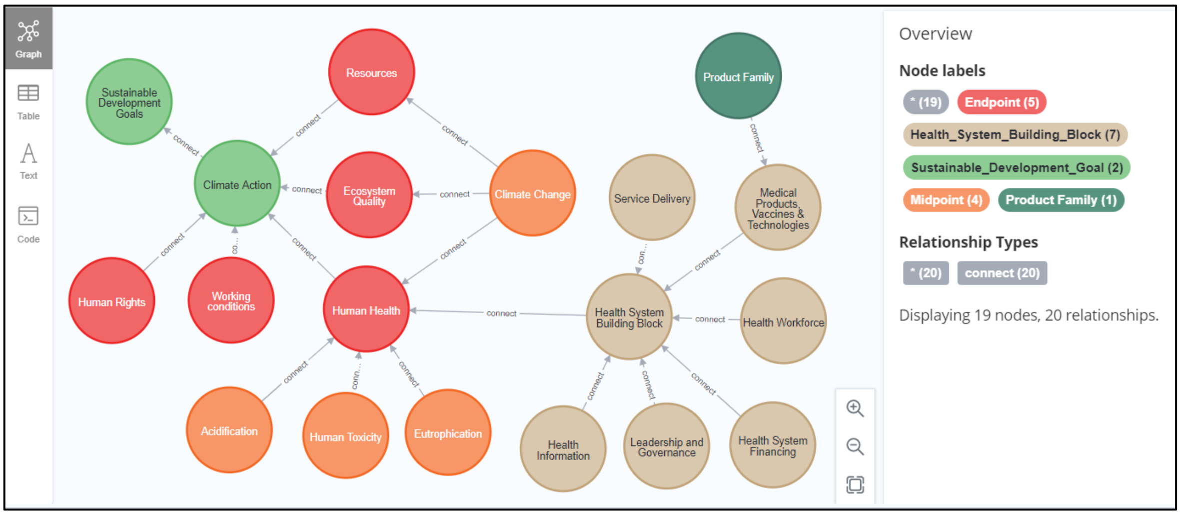

Figure 6. Exemplary excerpt from the Engineering Graph

The two examples given show how the provision of a rich dataset in the early design phases can support design decisions. Taking the right decisions in early phases is not only important out of economic necessity, but also helps to reduce the ecological footprint because the impact from later phases can already be considered.

5 DISCUSSION AND OUTLOOK

This paper continues the research stream to build, extend and use the Engineering Graph to support product development. It is shown how the graph connects data from external sources to increase system knowledge and to add context information to product data. One specialty is the ability of the Engineering Graph to provide large amounts of connected data in the early design phases.
The Engineering Graph is used to support design decisions when setting up development projects and within a development project. It is shown that taking good decisions in the early phases of product development is especially important because here the impact of decisions is highest, design flexibility is high and resource commitment is low. Therefore, the design and the product success can heavily be impacted by good decisions in the early phases.
Finally, two examples are presented how the Engineering Graph supports design decisions in the medical device industry. The first one shows the support during product development when an existing product shall be approved in a new market. The second example shows how the setup of a development project for a new product is supported.
One limitation of the paper is that the use case comes from only one industry. Therefore, the Engineering Graph needs to be applied to more industries and prove its usefulness. Industry specific sources need to be researched and added to the graph to provide a full picture of the system context for other industries as the medical device industry.
Further research should apply the Engineering Graph to different industries and companies. Additionally, the graph needs to be extended and more and more sources need to be added to the graph. A study to validate the economic usefulness needs to be conducted to understand in which cases the effort to build and maintain the Engineering Graph is justified.

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