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MODEL-BASED SUSTAINABLE PRODUCT DEVELOPMENT

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1. Introduction

Within the last three decades, a large variety of frameworks, methods and tools have been developed for supporting the integration of sustainability aspects into product development. The majority of approaches focuses on assessment and provides a basis for further decisions. For supporting design synthesis generic guidelines are most commonly utilized. Nevertheless, in spite of all research efforts performed in the field of sustainable product design, the ability of engineers to get an overview of the systemic consequences of their decisions on the multiple dimensions of sustainability, in particular in the early design phases, leaves potential for improvement.

This paper introduces an approach for formalizing the system dependencies between sustainability impacts, design principles and product properties, hence supporting engineers predicting the complex and unintended consequences of the decisions they make along the product development process. This approach aims at allowing engineers for testing the effects of given decisions and at exploring the solution space constrained by given sustainability targets, hence supporting them in the development of more sustainable products.

After a short overview of the field of sustainable product development in Section 2, Section 3 introduces a framework describing levels for describing sustainability effects of product development decisions. Based on this framework, Section 4 presents the new approach "Model-based Sustainable Product Development" making use of formalized system dependenices between model levels in order to evaluate the consequences of a design decision and to explore the solution space allowed by a given set of constraints. Section 5 illustrates this approach on the example of a bicycle frame before conclusions are drawn in Section 6.

2. Sustainable Product Development (SPD) - overview about the current state

In order to cope with the complex interrelations between the product's lifecycle phases and sustainability dimensions, a large variety of design methods has been developed over the past thirty years. In 2002 already, Bauman, Boons and Bragd identified 150 methods and tools for environmental product development. Several literature reviews and overviews have been produced in this field (e.g. [Bovea and Pérez-Belis 2012]). Available approaches can be classified in six categories: Frameworks, checklists & guidelines, analytical assessment & rating/ranking tools as well as organizing tools and software/expert systems [Baumann et al. 2002]. Frameworks are more general "schools of thought", like "Ecodesign" for example. Checklists & guidelines provide generic support for sustainable product development. They can be beneficial for designers which are not familiar with the topic sustainability or lifecycle considerations. However, due to missing specificity, these approaches can be less useful in concrete product-dependent decision situations [Knight and Jenkins 2009]. Quantitative-oriented analytical assessment methods, e.g. Life Cycle Assessment are already commonly utilized in industrial practice [Kara et al. 2014]. Since these approaches require a detailed set of information about the whole product lifecycle, they are usually applied when major design decisions are already made. In order to address this issue simplified LCA approaches were developed [Collado-Ruiz and Ostad-Ahmad-Ghorabi 2013]. Rating and Ranking tools (e.g. Material Input per Service Unit [Ritthoff et al. 2002]) are more focused on a qualitative or semi-quantitative comparison between different decision alternatives and require considerably less data [Baumann et al. 2002]. However, these tools tend to oversimplify the complexity of developing sustainable products and provide limited value for reproducible decision making. Software and expert systems help engineers to integrate sustainability considerations into their workplace. For example solutions which combine CAD and simplified LCA (such as EcologiCAD by Leibrecht et al. [2004] or Solidworks Stustainability) give a good understanding for fundamental dependencies between product design and selected environmental indicators on a trial and error basis. Trial and error refers in this context to a time-consuming manual adjustment of design parameters in many iterations until a satisfying solution is found. In order to mitigate shortcomings of individual approaches methodologies comprising several methods were developed. Dufrene et al. [2013] developed for an example a combination of LCA, Life Cycle Costing (LCC) and Guidelines. The corresponding platform is integrated into the engineering workspace. Romli et al. [2015] presents a similar (but less integrated) approach based on Case Based Reasoning and Quality Function Deployment. The consideration of sustainability aspects with systems engineering methods is with a few exceptions still a white spot in the research field. Eigner et al. [2014] use for example SysML to integrate sustainability data in the context of their System Lifecycle Management approach for sustainable product development. Nevertheless, the approach is currently solely focused on the usage phase without considering the whole product lifecycle.

What most existing methods for SPD have in common is a concentration on support of design analysis. Synthesis is currently provided by guidelines or trial and error based quantitative approaches. Currently missing from the author's perspective are automated and knowledge-based approaches for considering sustainability related design targets in the early phase of product development. First studies were made to evaluate the potential of ontologies to link sustainability targets and technical requirements to material decisions (see [Stark and Pförtner 2015]). This article builds upon these insights and explores the necessary scientific basis for considering more comprehensive use cases such as selection and combination of solution principles to sustainable design concepts.

3. Linking product characteristics with sustainability impacts

In order to increase the transparency of decision making in the context of sustainable product development a framework for describing the causal influences between engineering decisions and sustainability impact is necessary. As a basis for a formal representation of engineering decisions the established concept of Property Driven Product Development (PDD) (see part 3.1) is combined with indicators for measuring the environmental, economic and social dimension of sustainability (see chapter 3.2. PDD was chosen as a basis since it puts a clear focus on the differentiation of cause and effect of engineering decisions.The resulting framework (see chapter 3.3) identifies different levels of what Weber et al. [2003] call product properties. This increase of resolution does not specify a development methodology by itself. It rather allows to identify different levels for describing sustainability effects of product development decisions. These levels range from pure technical attributes based on the laws of physics to the whole product lifecycle which includes additional influencing factors like user behaviour or legal constraints. The identified levels allow a more systematic description of the dependencies and interfaces between attributes which are determined by different stakeholders (e.g. component or system engineer, environmental expert) in the company and require different types of information, IT systems and decision support models. Hence, this framework can be used complimentary to existing design models such as the Function-Behaviour-Structure Model [Gero 1990] or Axiomatic Design [Suh 1990]. Furthermore, it builds the theoretical fundament and the necessary terminology for the model-based approach described in section 4.

3.1 Property Driven Product Development (PDD)

One of the foundations for the evaluation of dependencies between engineering decisions and sustainability impact is the stringent differentiation between product characteristics and product properties defined by Weber et al. [2003] and illustrated by Figure 1. Product characteristics (also referred to as "design parameters" [Suh 1990]) can be directly influenced by development engineers. Examples are geometry, material, surface characteristics, tolerances or definition of technology. Product properties (or "functional requirements" [Suh 1990]) are resulting from a combination of characteristics and constitute the product’s behaviour (e.g. functionality), its external reception (e.g. aesthetics) and suitability for a defined usage context (e.g. maintainability). The delineation between product characteristics and properties enables a finer definition of the analysis and synthesis cycles required by product development as well as an enhanced tool support. Based on this, Weber et al. [2003] developed a generic approach, named "Property Driven Product Development". Figure 1 shows exemplary characteristics and properties on system, assembly and part level. What can be considered as missing in this overview is the influence of control algorithms and software-intelligence for mechatronical products which gained importance within the last years (especially in the context of cyberphysical systems). PDD has been further specified for different applications, e.g. Product Service Systems [Weber et al. 2004]. Currently, there is no adaption of PDD for sustainable product design. Hence, this gap will be closed in chapter 3.3.

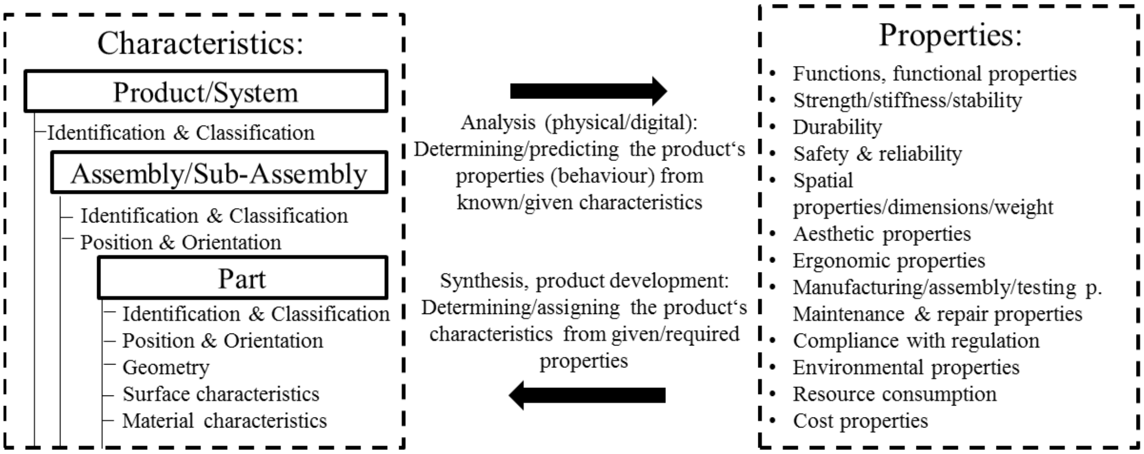

Figure 1. Product characteristics and properties, own representation based on [Weber et al. 2003]

3.2 Sustainability indicators

Along with the development of Life Cycle Sustainability Assessment (LCSA) as a method for measuring the sustainability of a product or a system, a wide range of sustainability indicators have been made available (an overview is for example given by Singh et al. [2012]). Although LCSA aims nowadays at encompassing all dimensions of sustainability (environmental, economic and social assessment) [Finkbeiner et al. 2010], the quantitative assessment of products regarding their lifecycle impact has its origins in the environmental sciences with a primary focus on Life Cycle Assessment (LCA). Environmental assessment has a long history, is the object of international standards (e.g. [International Organization for Standardization 2002]) and is widely implemented in industry.

Economic aspects are considered primarily by considering cost (manufacturing or life cycle costs) [Finkbeiner et al. 2010]. Life Cycle Costing (LCC) is a mature approach that allows assessing all the costs occuring along the product lifecycle (e.g. [Goldman 1969]). Research about social sustainability is still in its infancy. Finkbeiner et al. [2010] state for example that social indicators are not directly applicable for products or processes and need to be adapted first from other reference levels (e.g. regions or organizations) via assumptions. Typical impact categories considered in Social Lifecycle Assessment are human rights, working conditions, health & safety as well as corruption, discrimination and child labour [Ciroth et al. 2011].

The operationalization of the large variety of available indicators in the context of product development is a rather difficult task. A large share of available indicators is aimed at supporting transparency at corporate or industrial sector level, and is therefore hardly applicable for measuring product-related sustainability impacts. Some authors are adressing this challenge by developing indicator sets which are customized for product design. Nevertheless, it is not always clear for designers how they can have an influence on these criteria. Shuaib et al. [2014] adress for example the criterion "Logistic Cost" as a part of the "Product Sustainability Index". In order to evaluate which design can be beneficial for saving logistic cost additional information is necessary (e.g. influence of weight and geometry on fuel consumption of the transportation fleet). If these relations are intransparent to product development engineers design synthesis in early phases of product development is hardly achievable.

3.3 Levels for describing sustainability effects of product development decisions

This section introduces a framework consisting of levels for describing sustainability effects in sustainable product development, from the narrowest (product characteristics) to the broader scope (sustainability impact). The approach of PDD (see chapter 3.1) was taken as a starting point to directly link sustainability impact with product development decisions. The interface between PDD and the lifecycle view of sustainability impact categories and indicators needed to be created for that purpose. The result of this process is a layered model which divides the category "properties" in three subsets (IIa-IIc) to show the transition from pure technical product properties to properties which include a lifecycle view and are the basis for sustainability assessment. The framework levels (see Figure 2), are enriched with examples which shall not be considered exhaustive. The levels are described hereafter:

- (I) Product characteristics specify all aspects of the product which the engineer can directly influence (e.g. geometry, material, control algorithms) (see chapter 3.1 and [Weber et al. 2003]). Product properties are subdivised here in three subcategories:
- (IIa) Technical properties are directly linked to characteristics via physical dependencies. The property "stiffness" is for example defined by geometry and material. Another example is the definition of thermal efficiency of a turbocharger by adjustment of software algorithms for control of a variable turbine geometry.
- (IIb) Lifecycle phase-oriented properties are addressing the suitability of the product design for a given purpose related to a given lifecycle phase (e.g. maintainability, upgradeability). They can be directly determined via a combination of product characteristics (e.g. has the geometry a strong influence on products aesthetics) or indirectly via technical properties (e.g. durability is influenced by stiffness, strength & stability). Lifecycle phase-oriented properties can also be understood as design goals (e.g. DFX) or implimentation principles/strategies.
- (IIc) Lifecycle-oriented properties are measures which reflect the interrelation of a product with its surrounding systems along the entire lifecycle. They are the result of a Life Cycle Inventory, which measures all ingoing and outgoing flows (e.g. mass, energy, emissions, cost) along the product lifecycle. They can be directly determined via a combination of lifecycle phase-oriented properties (e.g. durability influences the product lifetime and therefore could influence CO2 emissions if the product must be replaced less often).
- (III) Sustainability impact as defined in chapter 3.2 reflects the impact of lifecycle-oriented properties on stakeholders (e.g. customer, environment, company etc.).

Figure 2 furthermore shows qualitatively the scope of influence of engineers and other stakeholders on the five levels of the framework. The influence of the engineer decreases while the influence of other stakeholders (e.g. manufacturing department or user) increases with every level. For example, the technical property weight is a direct result of decisions in the design process whereas the lifecycle-oriented property product quality is also influenced by sourcing and manufacturing operations. Furthermore, the uncertainty for prediction of the impact of engineering decisions increases with every level since more and more assumptions need to be made (e.g. prediction of user behaviour). In reality the dependencies between the examples depicted within the levels of Figure 2 are much more complicated and would rather appear in the form of a network than in the strict linear form in the given framework.

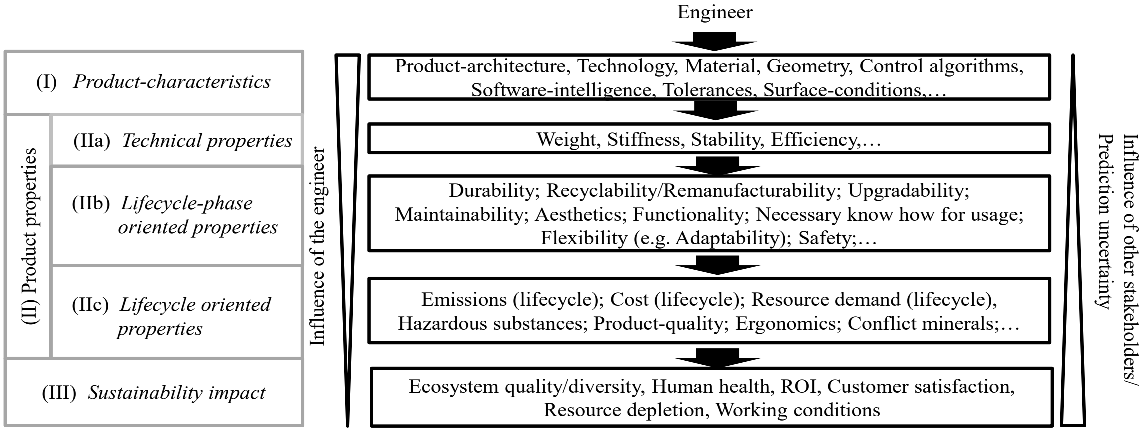

Figure 2. Framework for describing sustainability effects of product development decisions

The model was therefore instantiated for several examples in order to study the dependencies within the levels and to evaluate the validity of the classification. A comprehensive example for instanciation of all levels can be found in Figure 3.

Moreover, the potential of these models for decision support in the early design phases is discussed in chapter 4. The approach of Model-based Sustainable Product Development is introduced and possibile use cases for system dependency models are presented on the example of a turbocharger.

4. Model-based Sustainable Product Development

Model-based Sustainable Product Development stands for an approach which focuses on enhancing the ability of design engineers to evaluate the consequences of design decisions on sustainability targets and to explore the solution space allowed by those targets. This approach is based on a systematic development and application of dependency models capturing relations between system elements with regard to the framework developed in chapter 3. Figure 3 illustrates this concept on the example of a turbocharger. It displays dependencies between different components of an exhaust gas turbocharger embedded in a passenger car and selected lifecycle impact categories. The dependencies within the displayed concept map are simplified by arrows. In chapter 5 an example is given how these dependencies can be formalized based on ontologies.

The concept map only shows an extract of the actual dependencies of a real system. Nevertheless, it already illustrates the complexity of estimating sustainability effects of turbocharger design decisions. Due to this complexity it may not be feasible to adress all levels of the above introduced framework in one model. The model in Figure 3 is therefore split into two parts. The upper part (from sustainability impact to lifecycle-phase oriented models/technical properties) reflects the domain of the sustainability expert who defines the most sensitive areas of influence for sustainability improvement of a product.

In the case of the turbocharger typical "sustainability hotspots" would be for example the CO2 emissions of the car, where the turbocharger is integrated or carcinogen Nickel compounds affecting the health of workers in production. It is also possible to define hotspots on the level of technical properties (e.g. weight) depending of the corresponding Life Cycle Sustainability Assessment study (see chapter 3.2). The lower part of the model (from now on refered to as system dependency model) relies more on engineering expertise and focuses on the dependencies between engineering decisions for adjusting product characteristics and the consequences on aforementioned sustainability hotspots.

Hence, one focal point of Model-based Sustainable Product development will be directed towards estimation of design decision consequences on given hotspots in the form of design targets.

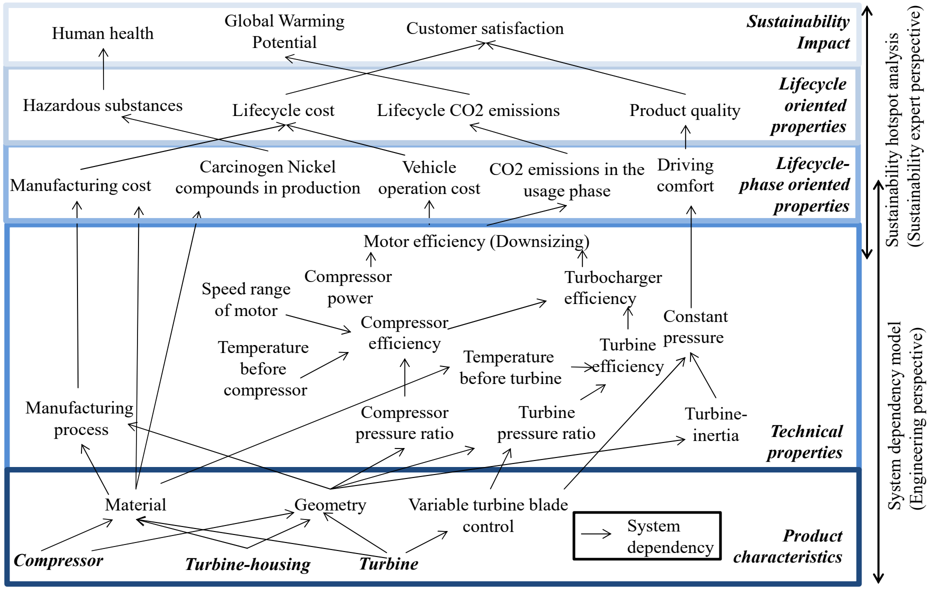

Figure 3. Concept map of design influences for the development of sustainable turbochargers

For example, a change of material from Inconel718 to Titanium aluminide for the turbine blade leads to decreased turbine inertia. This change improves the dynamics of charging pressure and thus decreases emissions (in diesel engines). Additionally, the driving comfort is increased due to strong boost in areas of low engine- speed and Nickel (a major part of Inconel), which is partially carcinogen, is substituted. Titanium aluminide is more expensive compared to Inconel. A trade-off decision regarding the relative importance of CO2 emissions, driving comfort and human health against manufacturing cost needs to be made. Assuming that sustainability targets are set on properties mapped in the system dependency model, such a system dependency model can be used in order to identify if design decisions contribute positively to those targets.

System dependency models can not only be used for identifying if given design decisions contribute positively to defined sustainability targets: they also allow an automatic exploration of the solution space allowed by those targets. If, for example, absolute targets for manufacturing costs and CO2 emissions are defined they need to be allocated to the respective components of the turbocharger. In this case, the turbine-housing as the most expensive and CO2-intensive component of a turbocharger would be considered. Influencing component characteristics (e.g. wall thickness) can be identified based on their relative influence on sustainability targets (via sensitivity analysis). By decreasing wall-thickness both sustainability targets (manufacturing cost and CO2 emissions) can be addressed at the same time by material savings. However, if the wall thickness of the housing passes a threshold, the component needs to be manufactured by investment casting instead by cheaper sandcasting leading to less emissions but higher cost. If the wall thickness is further decreased, a level of technical constraints for strength of the housing will be reached. Another example is the targeted achievment of driving comfort which is realized by supply of constant pressure also at lower engine speeds. Solution options could be a bi/twinturbo system involving two coupled turbochargers or a variable turbine geometry for better utilization of the exhaust gas flow. Depending on additional targets (e.g. CO2 emissions or cost) either one or the other solution can be beneficial. A system dependency model shall in this case assist an automatic discovery of solution-variants which fulfil technical constraints and are compliant to the given sustainability targets at the same time.

In contrast to existing LCA-based approaches, model-based sustainable product development does not focus on the accurate assessment of product sustainability but on the identification of the intended or unintended consequences of design decisions. However, this approach can be used complementary to LCA, which can be used for defining "sustainability hotspots" of reference products and allow setting sustainability targets for the product development project.

Figure 4 illustrates a possible application of the introduced approach in engineering decision support tools. It shows a tool interface displaying the abstract representation of a turbocharger's functional carriers together with their physical and thermodynamical dependencies. The engineer can select between different product configurations (e.g. simple compressor vs. additional exhaust gas utilization) and choose between different solution principles for realizing functional carriers (e.g. axial vs. radial turbine). Furthermore, the tool allows defining target values at different levels of the framework introduced in Figure 2. Based on these targets, the tool assesses the current configuration and also produces recommendations for configurations of the turbocharger that fit in the frame allowed by those targets. It can be decided whether the whole lifecycle or selected phases are considered. The system dependency model depicted in Figure 4 provides the backbone of the decision and links the selected configuration to a target dashboard. Furthermore, a library with different solution templates (e.g. axial turbine) is necessary.

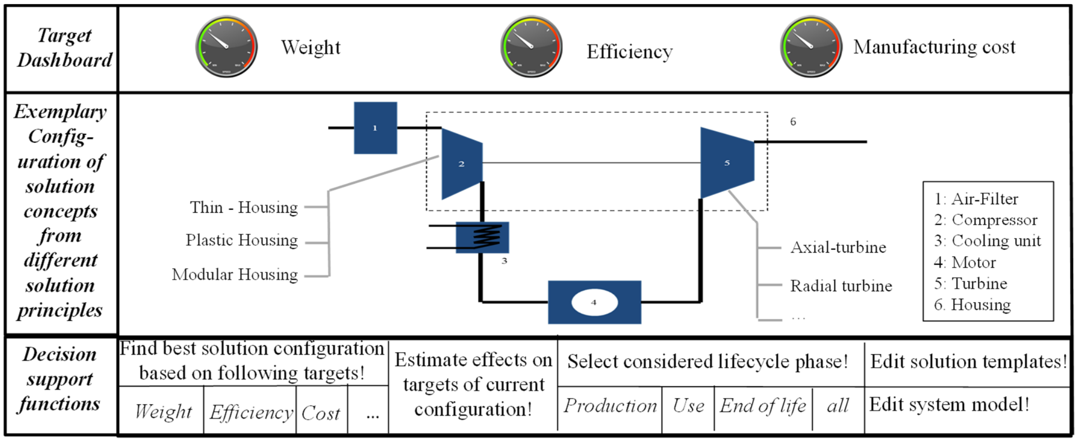

Figure 4. Vision for decision support interface for design and system engineers

This example illustrates the possible use-cases of system dependency models in sustainable product development. Nevertheless, it needs to be specified how the described system dependency models can be systematically build and applied for fostering decision support in design. In this context it also needs to be clarified where the necessary knowledge for model design can be derived from. The following section presents a case study addressing these challenges.

5. Example for modelling system dependencies

Formalizing system dependencies for identifying the efficiency requires comprehensive models. To limit complexity for a first case study, a bike frame was analyzed. The purpose of this study was to identify how suitable materials can be selected from a database based on given absolute sustainability targets and technical requirements. An LCA study has revealed emissions for wrought material production as an important lifecycle phase oriented property [Neugebauer et al. 2013]. Hence, the indicator "CO2 emssions in material production" was selected as a sustainability target for improving the bicycle frame. Furthermore, the durability of the bicycle frame in the use phase was chosen as a second target. The frame-durability determines a part of the value provided to the customer and may contribute to an overall reduction of CO2 emissions if the lifetime of the bicycle is extended. Another reason for chosing durability as a target is to verify that a material decision does not negatively affect the use-phase of the bicycle frame. The accurate determination of the frame durability would require a combination of different models for simulation of dynamic and static stability, material and usage behaviour. Hence, durability was considered by a simplified analysis of influencing properties (frame deformation and tensile strength). Figure 5 displays the system dependencies between durability and CO2 emission in material extraction with the product characteristics material and geometry. Each lifecycle oriented property depends on influences from the respective lifecycle phase and on one or more technical properties. Durability is dependent on the stiffness of the frame and on forces applied during use.

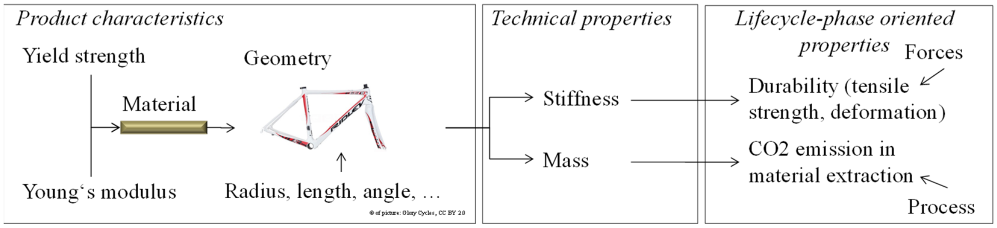

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Figure 5. System dependencies for a bicycle frame

CO2 emission in material extraction depends on characteritstics of the extraction process and on the quantity (weight) of the material used. The influences in a lifecycle phase are usually based on assumptions, e.g. based on user studies or empirical studies of similar processes. The relations between material parameters such as young's modulus and stiffness follow physical principles. The system dependencies can thus be captured in mathematical equations. However, determining the effect of the frame stiffness under certain forces for the entire frame requires complex calculations. Therefore, the deformation of the frame is in general approximated by numerical calculations based on material characteristics, geometry and forces. The relevant relations for the case of the bicycle frame were captured in an ontology depicted in Figure 6. The geometry and forces were captured in an finite elements method (FEM) model associated to the product component. An external FEM program, NX with the solver NX Nastran, was linked to calculate the deformation. The tensile strength is determined by the yield strength of the material and the maximum stress occuring in the frame based on defined forces and a defined geometry. Similarily, a link to NX is modeled to determine the maximum stress. For calculating the CO2 emission, formulas can be directly stored in the ontology. The CO2 emission is calculated by mass times the constant CO2 emission/kg for a specific material which can be derived from environmental databases. The mass in return can be calculated by volume times density of a material. The calculation of a geometry's volume also requires complex calculations. The volume was thus linked to a CAD program which calculates a volume for a given geometry. The model was serialized in an ontology to allow for flexible integration of new concepts (e.g. integration of new targets, databases etc.). A software tool named Sustainability Advisor (SA) was designed to extract and interpret relations. A parser was used to analyze formulas. The SA directly retrieved values from a database or a software tool, where applicable. The European Life Cycle Database (ELCD) was chosen to gather environmental data. Materials were gained from the embedded Siemens NX material database. The test case delivered several materials which fullfilled the CO2 Emission-, strength- and deformation targets. However, materials had to be excluded from analysis (e.g. anisotropic materials) which would have required a non-linear FEM analysis and thus a significant higher formalization effort to automate the analysis.

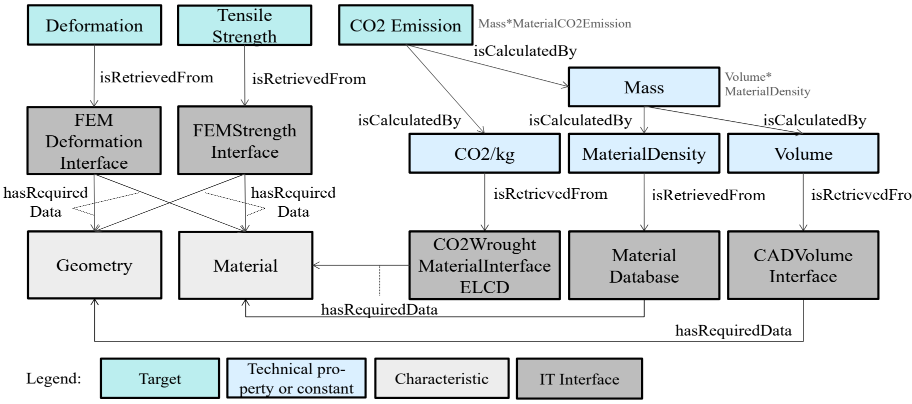

Figure 6. Formalization of system dependencies

The analyzed cases discussed in the paper provided the following findings concerning the challenges identified in chapter 4:

- System dependencies can be mathematically formalized based on physical relations and on empirical studies to automatically determine lifecycle (phase) oriented product properties
- Much information on system dependencies is already encapsulated in different models and programms (e.g. the calculation of the volume in a CAD program). A meta or master model can combine knowledge of different models (e.g. realized in an ontology). System dependencies can be either stored in the meta model or in models distributed in different product development expert tools (e.g. CAD, FEM Model)
- The ELCD only has limited datasets and mapping to NX materials was thus imprecise. The choice of database and an accurate mapping of materials hence affects the validity of results.
- Approximating physical relations may reduce the modeling effort, e.g. to determine the efficiency of a turbocharger, especially in early phases of design. However, further research must clarify to which extent calculations can be simplified and still provide significant insides.

Additional information about ontology based models for decision support in sustainable product development are provided by Stark and Pförtner [2015].

6. Discussion and conclusion

The presented approach focuses on enabling design engineers to develop more sustainable products by providing enhanced possibilities for modelling consequences of design decisions. A framework was presented which provides a classification of dependencies between product characteristics and sustainability impact. The framework provides a harmonized nomenclature for sustainable product development and could also be used for teaching for example. The levels of the presented framework described in section 3 are formulated in a generic way (Figure 2). In order to achieve convincing decision support for design engineers, they require adaptation to product-specific contexts and the relations between the different system elements need to be described.

As shown qualitatively in chapter 4, product-related sustainability models can be utilized for trial and error based analysis in order to evaluate unintended side effects of engineering decisions within and between sustainability dimensions along the product lifecycle. Furthermore, design synthesis can be enabled by using models for direct identification of product characteristics and solution concepts based on given targets (e.g. automated identification of suitable material variants).

An exemplary case study showed how system dependency models can be quantitatively formalized with ontology models to offer synthesis based on sustainability targets and technical requirements. It proved that it can be beneficial to couple different IT systems and product models in order to reduce modelling effort and to provide a realistic estimation of product properties (e.g. durability) for further analysis with LCA or other assessment tools. However, there were also many obstacles identified which show that model based sustainable product development is still in its infancy. The associated complexity will be one of the largest challenges of the approach. The provided example described in chapter 5 consists of one component. More complex products including assemblies with mechatronic elements will be rather difficult to address. Moreover, the consideration of multiple functional requirements, in particular on geometry, requires a range of simulation models with their individual assumptions and limitations leading to large uncertainties of model results. Alternatives to simulation could be empirical values for approximating causal effects of design decisions. Further case studies and surveys with design engineers will be necessary to find the optimal degree of up-front decision support. These studies will also provide necessary data for model design and for validating model results and predictions in particular for synthesis of design concepts. It is furthermore still subject of research to provide engineers with the necessary knowledge in early phases of product design and to decrese effort for information search at the same time. In this context templates and design repositories can be used to simplify model application. In order to limit data requirements and to consider mostly qualitative social indicators at the same time, a mixture of qualitative and quantitative modelling could be beneficial.

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