Systematic Lightweight Design of Production Equipment with a Digital Toolchain

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Abstract. The importance of sustainable production is growing all the time. Lightweight design of production equipment is a possible measure to increase the sustainability. These potentials are often not used to their full extent due to a high focus on investment costs. To resolve this target conflict, this paper presents the lightweight design of production equipment based on a systematic development process and the corresponding digital toolchain. It includes a newly lightweight design technology planning tool to optimize cost, CO_2 and weight from a production perspective. Based on a rough description of the component and previously modelled requirements an optimized shape, production process and material are recommended. Subsequently, the component can be further detailed with this knowledge. Through the digital toolchain the effects of different designs on the usage of the production equipment can be easily estimated. This enables the developer to identify the potential of lighter but more expensive components.

Keywords: Lightweight design · digitalization · sustainable production

1 Introduction

Legal requirements for companies to report on sustainability indicators increase the importance of sustainable production. This requires sustainable machines and equipment in the production. To achieve this, the machines and systems must be designed to be both energy-efficient in operation and able to be produced in a resource saving manner. This leads to an increasing pressure for the machine and production equipment industry to improve the sustainability. Like in the automotive or aerospace industry where additional costs are accepted for lighter and more efficient products lightweight design has great potential to increase the sustainability. The realization of this potential is limited by the high time pressure in the engineer-to-order market and the customer's unwillingness to pay more for lighter products. To solve the target conflict between costs and a reduced weight, to reduce the CO_2-Footprint of the product, the integration of the production and the material in the early design process as well as the usage of a continuous digital chain for the development is necessary. From the production perspective the center of the digital toolchain is a technology chain planning with focus on the evaluation of cost, CO_2 and weight. In Sect. 2, existing development approaches

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for an early integration of the production are presented. In Sect. 3, the developed digital toolchain for lightweight design optimized products is presented. Section 4 presents the application of the methodology to production equipment. At the end, a conclusion as well as an outlook is given.

2 Related Work

The development approach of the VDI 2221 [1] is a commonly used development process. It describes a systematic process for problem solving during product development and supports in structuring the development task. However, the development process integrates the production and the material late in the development process. This lead to expensive iterations and loss of time. Furthermore, this approach does not provide any specific methods for lightweight design. Therefore, several lightweight specific approaches were developed [1]. Klein [2] and Krause [3] developed a development process based on the VDI 2221 for lightweight design. During the requirements recording a guideline regarding the lightweight important loads is given. Additionally, lightweight specific optimization methods like topology optimization are integrated in the process [2, 3]. However, the approach does not support an early integration of material and production in the product development process. The development process by Hufenbach and Helms [4] supports an intensive interaction between product, production and material during the whole process and points out the importance of iteration during development of lightweight products. They integrated the interdependencies of product, manufacturing, joining technology and material in the development process and demonstrate the importance of an early integration of material and production in the development process [4]. The weakness of the process is the limitation to fiber-reinforced plastics instead of considering also other materials, production processes and product designs regarding CO_2, costs and resulting product weight. Furthermore, the process focusses on one part and is not considering the interdependencies between components.

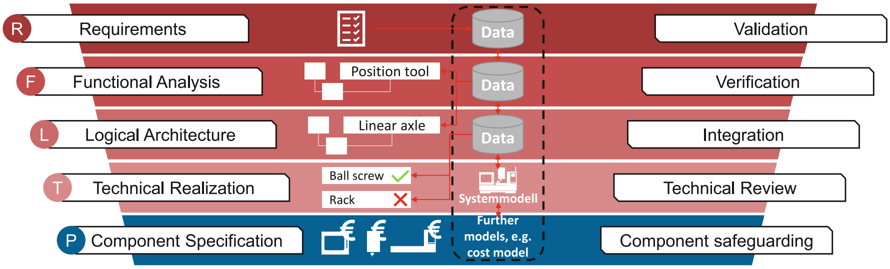

Fig. 1. MBSE approach for the use in production environments

For this purpose, a systematic lightweight development process was developed [5, 6]. The process is based on the concept of Model-Based Systems Engineering (MBSE). After an initialization with the definition of a target system that contains the goals for cost weight and CO_2, requirements are defined. In general, based on the requirements (R), firstly a functional view (F) on the system is build up. This is followed by a logical view (L) and a detailed physical view (P). The authors already extended this by a technical view (T) as the gap between L and P was found to be too significant (Fig. 1). The structure follows the well-known scheme of the V-Model [7] that gets extended by production, material and joining technology which are included along all development levels. The level of detail is increased along the process. The necessary iterations demand the process to being non time-serial while still maintaining the build-up of the development levels. Subsequently, system and process integration follow up before an acceptance test is carried out. For decisions along the development process, it is crucial to provide the necessary data regarding costs, CO_2 and weight and connect it to the product description in the several views.

For optimizing products from a production point of view early in the development process, technology chain planning methods are well known. Klocke et al. [8] define a technology chain as a machine independent combination of manufacturing technologies or manufacturing processes in a defined order for manufacturing a product. For generating technology chains, technologies are described with e.g., manufacturable materials, manufacturable tolerances or number of parts. This technology parameters are compared with product features like required tolerances or complexities which enables selecting suitable manufacturing technologies. The technologies are evaluated regarding the fulfillment of the product requirements. Afterwards, material, geometry or manufacturing technology are changed to improve the evaluation. Based on the fulfillment of product requirements after a manufacturing technology, further manufacturing technologies are added and alternatives of technology chains are generated [8]. This method has its limitations in not supporting the iterative design and in evaluating the manufacturing technology chains regarding factors like costs or CO_2. However, the methodology clearly shows the need of a rough description of product geometry to analyzing interdependencies between material and production. For this reason, the technology chain planning should be included in the technical view.

For handling the target conflicts of product function, costs and other criteria several approaches integrated multi-criterial decision making in the technology chain planning. For example, Müller [9] generates technology chains considering material parameters, number of manufactured parts, flexibility as well as ecological criteria for already designed products. The evaluation of this parameters requires a suitable database for analyzing the manufacturing technologies as well as a high degree of detail for the designed components. For the evaluation the Analytic Hierarchy Process (AHP) combined with Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) is used [9]. These two approaches are used in several approaches to find the best solution in case of conflicting evaluation parameters.

The approaches of Rey et al. [10] and Jacob et al. [11] identified the importance of iterative product design in combination with technology chain planning. Both of the approaches are able to deal with uncertain component parameters and do not require a fully designed component [10, 11]. Rey et al. considers classic manufacturing technologies in their approach. With Jacob et al. it is possible to generate hybrid technology chains with additive and subtractive manufacturing processes. Through the flexibility of additive manufacturing hybrid technology chains also show great potential for lightweight design. Furthermore, this approach uses a structured Unified Modeling Language (UML) - based requirements description model which shows great potential for integration in a systematic development process [10, 11].

All of the presented technology chain planning approaches show great opportunities for integrating the production in the early design process. However, each of the approaches are just able to optimize one component based on the requirements. The approaches do not consider interdependencies between components in case of weight changes of other components which effect the requirements on the optimized component. Furthermore, CO_2-emissions are not considered and the presented approaches are not integrated in an overall development approach which is continuously digitized. This leads to limitations in optimizing a system regarding cost, CO_2 and weight over its whole lifecycle.

3 Digital Toolchain and Technology Chain Planning

To address this limitation, a variety of methods has been implemented to support the systematic development approach. Starting point is a target system where development goals are set. These development goals for example are restrictions for the product e.g., costs and weight, as well as lightweight or sustainability specific requirements that allow the derivation of requirements of product, production and material. The target system sets the overall goal of the development for the whole product and weights the importance of the target figures costs, CO_2 and weight. After this strategy has been specified, requirements are derived and noted in the R-view. Here a functional hierarchy, a functional model and a minimal design propose possible methods that can be applied regarding the structure of the product. Existing reference products or previous product generations can be analysed via a modified function-mass-analysis to identify optimization potentials [12]. Based on the results components with great potential can be prioritized in the further development stages.

The effects of interdependencies between product design, production, material and joining technology can be analysed based on the knowledge from previous development cycles to detect compatibilities of functions and material classes. Knowing the functional level, the L-view can be started with the generation of possible solutions to the generated functional artefacts. The authors already proposed a lightweight creativity process [13] which proved suitable by embodying the iterative nature of product development. Through the breakdown of assemblies via taking a functional view along the paradigm of systems engineering, existing creativity techniques and evaluation methods for idea generation and evaluation have been analyzed and rethought from a lightweight and sustainable design perspective. The methods were tested on the later introduced use case from the field of robotics, which enabled the identification of the potential of LWCM for a lightweight and sustainable design. Following the creativity phase, more detail requiring methods find application. The T-view describes the rough dimensions of the solutions from the L-view. With the resulting rough geometry, a more detailed integration of the production is possible at this point. For this purpose, the later described technology chain planning for specific components was developed. Additionally, the design alternatives can be evaluated by one-dimensional simulation tools to identify the resulting energy consumption during usage.

For the implementation and the transition to the more detailed P-view, a lightweight specific construction catalogue and a method to quantify secondary effects of changes in a subsystem can be applied. In the P-view the level of detail of the solutions is very high. Therefore, very specific and specialized methods like multi criterial decision making, topology optimizations and multi body simulations can be carried out. Especially, during the topology optimization the information from the technology chain planning is used to set the design freedom and reducing the needed time. With this view exact numbers on cost, weight and (lifecycle) CO_2-emissions can be generated. Up until now, all these tools and methods coexisted and got applied uniquely for each task. Therefore, production was always integrated late into the product development process that took place. The reason for this was the strongly limited linkage between the methods and therefore the difficulty of creating a process chain. This showed the need for interfaces between the methods. These interfaces got addressed in the project SyProLei. Here, the whole process from the requirements up to the physical design was digitalized and linked continuously. The continuous link to production hereby represented a large difficulty. Especially the link to and integration of technology chains had not yet been created.

Digital continuity is essential for a flexible, robust and most important weight, CO_2 and production considering product development. The vast variety of methods and their different implementations as well as necessary requirements, inputs and outputs make the connection and continuity of the process difficult to achieve by means of the tools themselves. Therefore, an instance of coordination and data handling on a superior level is necessary. For this purpose, a Product Lifecycle Management (PLM) system like Siemens Teamcenter can be used [14]. In this environment, the systems modelling workbench (SMW) is used to model the functional and the logical view. These views are connected to the 1D-Simulationtool AMESIM, which enables the simulation of the behavior during usage. Furthermore, it is connected with the CAD-System Siemens NX for connecting the functions and logical elements with the geometry information. Connecting the information over the development cycle and saving them in a PLM system supports the knowledge transfer between product generations and the evaluation of solutions. With this extension, the MBSE-character can be implemented in Teamcenter as can be seen in Fig. 2. Furthermore, the definition of interfaces allows for an implementation of environment-foreign tools into the digital toolchain. The systematic development supports the engineer in connecting functions, logical elements and the resulting components. Furthermore, impacts of other components on the currently designed component can easily be identified.

To integrate the production into the digital toolchain, an extended technology chain planning approach was developed and is integrated in the technical design. The considered component is described by requirements regarding loads and tolerances and the needed functions. Through the MBSE approach product features can be generated from the knowledge in the PLM system. Furthermore, the manufacturing technologies and the materials are modelled in a database, which is modelled with an UML-Diagram in Fig. 3**.** The manufacturing technologies are described by their process costs, manufacturable geometry features and the manufacturable materials. Beside the manufacturable complexity possible specific lightweight design options for each manufacturing technology are stored. Possible options are solid, hollow, sandwich, stiffeners and freeform.

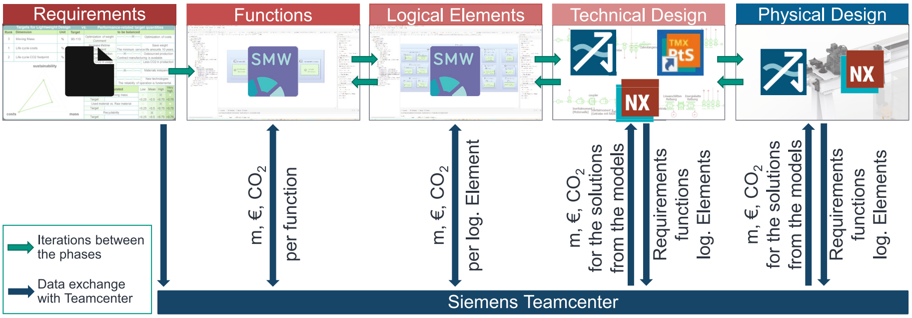

Fig. 2. Phases and methods and their implementation in the Siemens environment

Each of the materials are then described by the manufacturing process depending process energy for one kg material, the parameters of the material itself and information regarding the end-of-life to enable a evalaution over the whole lifecycle.

To generate technology chains, the component description is compared to the material and manufacturing database. Thus, suitable manufacturing technology chains are generated. These technology chains are evaluated regarding costs, resulting component weight, ecologic criteria and lightweight design potential.

The costs consider the material costs and the manufacturing costs. The material costs are including the purchasing costs based on the required material mass as well as the recycling costs. These are calculated based on the required recycling energy from the database and a cost factor per energy unit.

The ecologic criteria consist of the CO_2-Emissions for raw material production, production process and the recycling of the component material as well as the material efficiency and the recycling rate of the material. The material efficiency depends on the manufacturing technology and the recycling rate on the material and can be directly taken from a database. The CO_2-Emissions are calculated based on the process energy, raw material energy and recycling energy multiplied by a CO_2-factor.

Additionally, lightweight design is evaluated. The indicators are the specific strength and the specific stiffness of the material as well as the lightweight design indicator of the material. This indicator describes the suitability of a material for different load cases with a value between one (bad) and five (good) [2].

Due to the different units of the indicators all of them are normalized to a value between one (bad) and five (good). The evaluation criteria are resulting in a target conflict. For this purpose, the TOPSIS algorithm is used for the evaluation of the solutions.

Furthermore, the construction options are assigned to specific load cases so that they will be selected based on the requirements. With this connection between manufacturing technology and construction principles, the engineer gets ideas how the component can be improved considering the optimized technology chain. Furthermore, the solutions are directly evaluated regarding their costs and CO_2-emissions. This helps identifying the potential of solutions.

After an initial generation of technology chains, the approach enables two optimization approaches. With the first one, an optimization can be started which varies product parameters like dimensions, material or technologies to find better solutions. The other

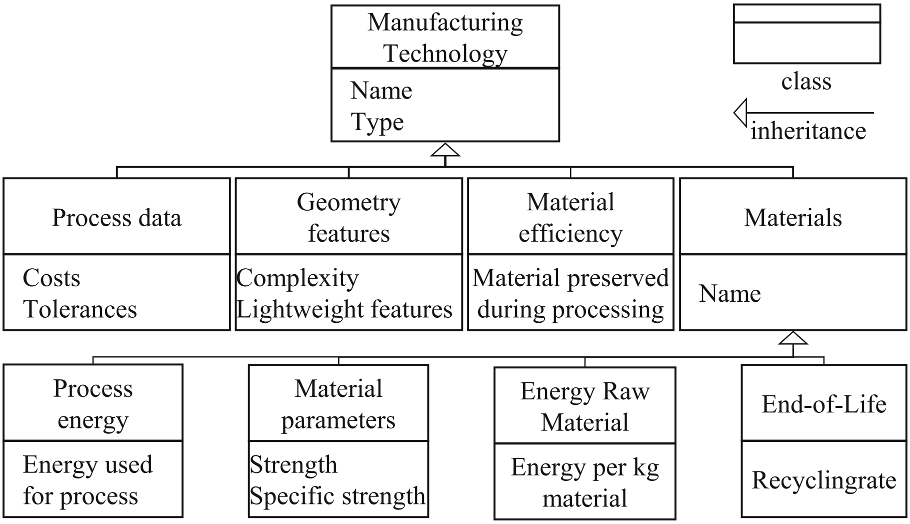

Fig. 3. Description of the manufacturing technologies and the materials for the technology chain planning

optimization approach enables the user to analyze how other components effect the costs, weight or CO_2-emissions of the component. For example, the loads applied to the component can be reduced by 5%, 10% or 15%. To achieve this reduction, changes to other components are required, but this approach allows effects to be identified even during manufacturing. This is enabled by the continuously digitalized toolchain.

The result of the technology chain planning is the optimized description of component dimensions and features as well as the material and the required manufacturing technologies. Furthermore, the component is described with its weight and its costs and CO_2-emissions during production and disposal. The information regarding dimensions and features can be transferred to a parametrized CAD-Model in Siemens NX which can be used for further development steps in the P-Phase like topology optimization.

4 Case Study

The system to be optimized in the case study for a further product generation is a portal robot designed to transport and load a tool between a tool storage and a machining center. Therefore, a robot equipped with a gripping system is mounted on a linear axis portal that spans from the furthest machine to the tool storage. The movement of the system demands energy and therefore produces CO_2-emissions. To minimize these emissions, a system with the optimum of production emissions and weight (emissions of time in use) should be targeted. As of now, the focus will be set on the robot and further downstream systems.

Initially the requirements were investigated and found to be covered fully. On this basis a functional model of the robotic system was build using the SMW. It was found, that the current product featured some parts that are not necessary by means of the functional model. Applying the FMA using the information stored in Siemens Teamcenter, it could be shown, that out of the in-house produced parts especially the gripping system introduces a lot of weight into the total system by requiring adapter flanges to fit onto the robot. As shown in Fig. 4, mass and CO_2 emissions of the function “Connect to the robot” should be decreased (red arrows), while costs can be increased (green arrows) until a target value (black line) is reached. This black line represents the relative amount of the costs permitted in relation to the relative importance of the respective functions.

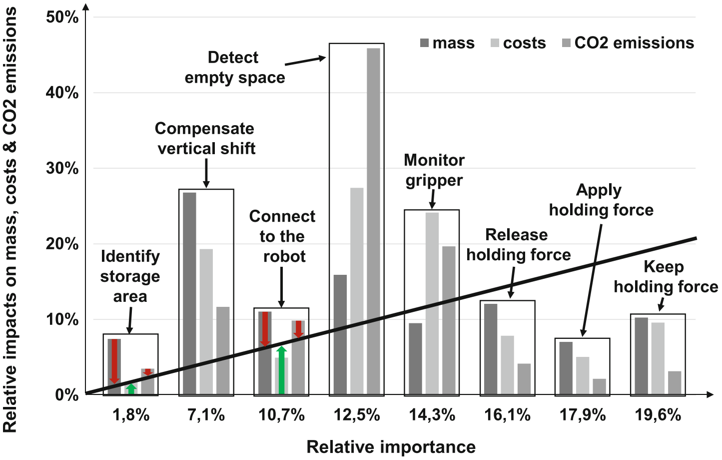

Fig. 4. Extended function mass analysis (example: portal robot) [6]

As a next step to optimize the system for minimal cost and emission, two paths could be followed. Firstly, new gripping ideas could be generated via creative processes. This has been done in [13]. Therefore, the focus of this paper lies more on the optimization of the identified parts and the effects of this process on the total system. As function to optimize “Connect to the robot” of the gripping system was chosen. This is realized with a flange. The requirements of the system are brought down to the specific component as well as the resulting requirements from related components like forces. Through experience knowledge it is identified based on the function and the requirements the number and position of drilling holes and the rough geometry. This information is translated to the requirement model for the flange which consists of number of holes, permissible installation space, required tolerances, applied forces, surface quality and hardness. Furthermore, a parametrized CAD-Model is generated with the important features, so the information of the technology chain can be easily translated to the CAD-model. With this information the design, material and technology chain are generated and evaluated as described in Sect. 3. For a better visualization of the strengths and weakness of different solutions a spider diagram like in Fig. 5 is used. For the presented solution in Fig. 5 the solution is very good regarding ecologic criteria as well as for the weight and the lightweight design. The solution lacks in costs. The selection of a component needs to be made with the weights of the target system. Based on the generated CAD-model, a topology optimization for example is carried out with considering the resulting design restrictions of the technology chain which leads to faster development times and better results.

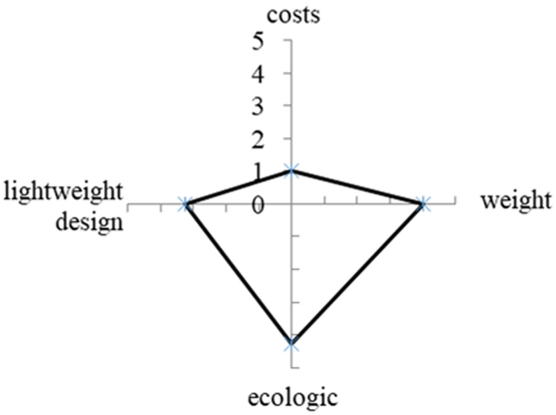

Fig. 5. Visualization of the results of the technology chain planning for Selective Laser Melting with Aluminium (0 – bad, 5 – good)

5 Conclusion

To overcome the target conflict of CO_2, costs and weight especially in industries with high cost pressure like the machine and plant engineering a digital toolchain which enables an early integration of the production in the development process. For this purpose, the paper shows a digital toolchain based on the Siemens Teamcenter with a technology chain planning which enables the user to analyze interdependencies between components and taking into account effects on the whole lifecycle of a product. To improve the technology chain planning in the digital toolchain it will be necessary to build up a database which includes a connection between product features and functions to support the early integration of the production.

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