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Multi-level modeling and simulation of manufacturing systems for lightweight automotive components

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Abstract

Hybrid lightweight parts aim at improving the economical and ecological performance of automobiles by reducing weight and, consequently, CO_2 emissions. The environmental advantageousness requires careful attention during the car's design phase to prevent problem shifting from use phase into production. Due to the degree of novelty of hybrid components, reliable data about energy and resource demands in production is not yet available. This work presents a multi-level simulation framework for coupling models from different disciplines in order to derive LCA-relevant data. Exemplarily, a discrete-event process chain simulation is connected with a physical process model for a forming process.

Keywords: Multi-level simulation; Energy efficiency; Hybrid lightweight design

1. Introduction

Automobiles enable individual mobility and are important means of transport worldwide. Automobile markets, especially in developing countries, are steadily growing and so are the related environmental impacts [1]. These impacts occur during each phase of the automobile's life cycle from the raw material extraction over manufacturing, use phase, to the end-of-life. Lightweight design is an approach to lower the vehicles' fuel consumption during its use phase which results in less emissions and/or an extended range being especially important for battery electric vehicles [2, 3].

Hybrid components are an approach to bring lightweight materials such as carbon fiber reinforced plastics (CFRP) into cars for the mass market. However, their ecological rucksack from material production exceeds the environmental impacts of conventional materials. The actual component manufacturing imposes an extra share of CO_2 equivalents to the vehicle. These negative impacts need to be compensated during the vehicles' use phase by a lower fuel consumption in order to reach the ecological break even [4] (see Figure 1).

As the energy and resource demand in manufacturing is largely defined in the upstream product design phase [5], knowledge about future demands needs to be made available at this early stage for decision support. Due to the high degree of innovation, the required environmental data is not yet available in life cycle inventory (LCI) databases which prevents valid life cycle assessments (LCA) for components and vehicles. As a result, the ecological advantageousness of hybrid components over their life cycle cannot be ensured.

Product development already requires the close cooperation of experts from product design, manufacturing and life cycle evaluation in order to identify the ecological, economical and technical optimum. Each expert employs specific software tools and generates data and models such as

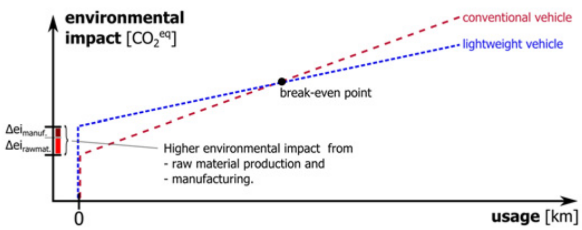

Fig. 1. Environmental impact of manufacturing

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CAD models during product design or energy and material flow models for production planning.

To overcome the aforementioned LCI data shortage, the proposition is to employ existing models from different levels of the manufacturing domain and to integrate them for LCI data prediction. This multi-level modeling is exemplarily conducted in the so-called Life Cycle Design and Engineering Laboratory at the Open Hybrid LabFactory (OHLF) which will be outlined in this paper.

2. Background

2.1. Hybrid lightweight design

In a vehicle, the engine works against the total drag force, which consists of the rolling friction, the force to accelerate, the upward slope resistance, and the aerodynamic drag. The first three parameters are influenced by the mass of the vehicle [6]. Thus, weight reduction is a key measure for car developers to reduce fuel consumption in the first place and to enable a downsizing spiral: Lighter cars require smaller engines which again reduce the vehicle weight [7].

One approach for weight reduction is *material lightweight design.* Classic materials like steel are substituted by materials such as aluminum or carbon fibre reinforced plastics, which allow the same part functionality at a lower part weight. Figure 2 shows the immense weight saving potential of new materials such as CFRP compared to state-of-the-art lightweight materials such as aluminum and conventional steel constructions. On the downside, the global warming potential (GWP) of CFRP is 17.5 kg CO_2^{eq} per kg of material [8] which is significantly higher than the respective figures for aluminum (11.5 kg CO_2^{eq}) and steel (2.8 kg CO_2^{eq}) [9]. Parts solely made from CFRP reach their ecological break-even point in cars after 85,000 to 13,000 km [10] which can exceed the vehicle's lifetime. An intelligent combination of these different materials in hybrid components thus makes sense from both an environmental and technical point of view.

The ecological performance of hybrid lightweight components based on CFRP depends on the amounts used of each material as well as the embodied energy from raw material production and component manufacturing. The impact from manufacturing strongly depends on the selection of technologies. Figure 3 illustrates that there are various process technologies, process stages as well as types, and materials.

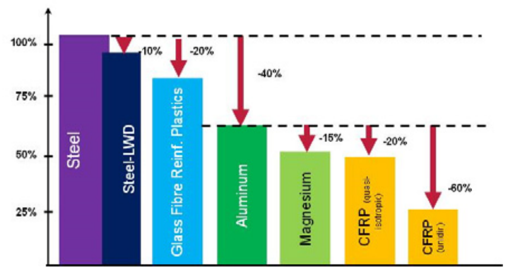

Fig. 2. Weight saving potentials for vehicles through material substitution while maintaining mechanical property, adapted from [8]

Inputs in the final processing are either raw materials, produced composites or pre-assembled work pieces (preforms) which are created during the in-between processing stages [11].

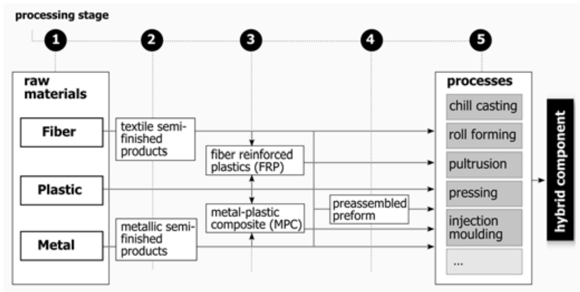

Fig. 3. Chart for structuring process chains, adapted from [Dröder2014]

As a consequence of this structure with different possible value streams for hybrid components, product and production planners have to evaluate each possible combination of materials, required processes stages and process technologies regarding economic and ecological objectives and constraints. For this evaluation, planners create and use models or simulation approaches as decision support.

2.2. Multi-level modeling and simulation

Simulation is a method for analyzing the behavior of a real-world system over time. A simulation model represents the elements of the system and the relationships of these elements. In simulation runs, the model is used to replicate the system's behavior and to generate results which can be transferred to the real system. Multi-level modeling and simulation describes the integrated representation and analysis of system elements from different levels of a system. A multi-level perspective can be realized by modeling different system elements within one model (model integration) or by coupling different models via interfaces. Multi-level modeling can also be realized within co-simulation approaches which couple simulation models of sub-system in order to realize an complete system simulation [12]. In contrast to an integrated model, each system element can be modeled in a different software program. That means, that co-simulation has important advantages [13]:

- Each system element can be modeled and simulated with the best suitable software,
- existing models can be re-used in order to reduce modeling effort, and
- single models can be replaced or modified without corrupting the entire system simulation.

There are various examples of multi-level approaches in the context of manufacturing systems. Overviews of simulation approaches for analyzing processes and the interactions between machines and processes for mechanical processing (e.g. grinding) can be found in [12, 14]. These approaches aim at an integrated analysis of structural machine behavior and the effects on processes, and vice versa. An approach for analyzing interactions between processes and process chains is presented in [15]. Thiede et al. developed a process chain simulation including different machine states and compressed air and steam generation [16]. This allows the integrated evaluation of the machine, process chain and technical building services (TBS) level. The research project ENOPA (Energy Efficiency through optimized coordination of production and TBS), aimed at the prediction of energy demands by coupling TBS and building models with a process chain simulation [17]. With a similar goal, Bleicher et al. presented a co-simulation environment for the optimization of energy efficiency in manufacturing systems. They combined models of machines, the energy system and the factory building shell with the help of middleware software [18].

3. Life cycle design through multi-level simulation

The advantages of multi-level modeling and simulation can only be realized if valid models and accurate data are available for each sub-system of interest. This means that it is important for experts from different disciplines to work closely. In the case of the development and manufacturing of hybrid lightweight parts, experts from product design and manufacturing have to collaborate to create combined simulation models and to collect required data.

The OHLF (http://open-hybrid-labfactory.de/) is a public private partnership for the development and manufacturing of hybrid components suitable for mass production. In the OHLF, the aforementioned collaboration of different disciplines is realized within the Life Cycle Design and Engineering Laboratory. The concept behind this lab will be presented in the next section.

3.1. Life Cycle Design and Engineering Laboratory

In the OHLF, many partners from industry and research collaborate with the goal to find product concepts, design guidelines as well as efficient process technologies and process chains for high quality and environmental friendly hybrid lightweight components for mass production. Since the goal of hybrid lightweight components is the reduction of environmental impacts over a vehicle's life cycle, it is necessary to consider the intended use cases and related expected environmental impacts in the early stage of product planning and design. In this context it is important to establish a transdisciplinary product development process. The involved disciplines are product planning, product design, design evaluation, process and machine planning, manufacturing system planning, life cycle assessment and life cycle costing. Each discipline uses different methods, tools and data sources for their specific tasks, which have to be able to be used collaboratively. A close collaboration and extensive information exchange between the involved disciplines is indispensible. Figure 4 presents the concept of the Life Cycle Design and Engineering Laboratory with the disciplines, methods, tools, and data sources.

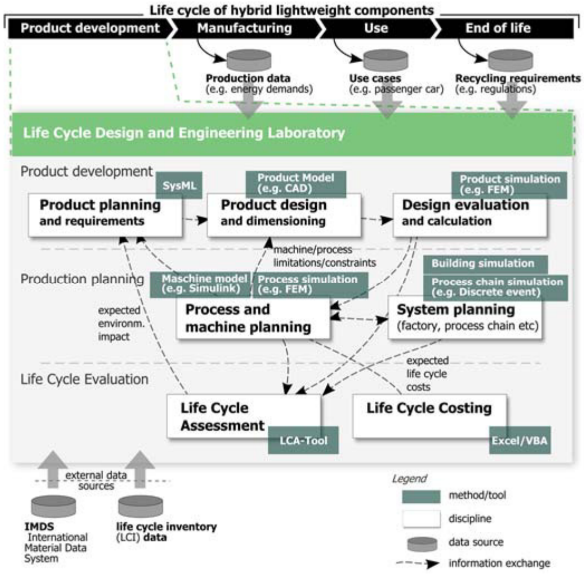

Fig. 4. Concept of Life Cycle Design and Engineering Laboratory

Data for life cycle evaluation comes from LCI databases, which are employed to cover the upstream processes in the supply chain. Furthermore, collected are more detailed data for the in-house processes. For example, the shop floor is equipped with sensors to record production data such as dynamic electrical load profiles. This, however, is only possible, if the machines are already available at the shop floor. If this is not the case, theoretical or empirical model or dynamic simulation models of machinery are used to predict production data. In order to create a holistic model for the prediction of life cycle impacts, data and knowledge from different disciplines have to be prepared and modeled to be used collaboratively. However, the development of one big model for life cycle impact prediction results in an enormous workload and holds the risk of omitting relevant expert knowledge which has priory been included in the specific model. Instead, the key to reliable integration with little effort is the coupling of existing models. For this purpose, developers and planners need to know which interfaces and connections have to be established and which variables have to be exchanged between models. This requires a framework for structuring different (simulation) models.

3.2. Multi-level simulation framework for manufacturing

The goal of the framework is to support production planners in defining required models of manufacturing system elements and to consider required interfaces for inputs from and outputs to other models. The included models are mainly from the disciplines product design, process and machine planning and production system planning. Inputs to the product design come from product planning and the determined results are inputs to the life cycle evaluation.

The elements of manufacturing systems can be allocated to different hierarchical levels of the manufacturing systems. Concepts for describing the hierarchy of manufacturing systems are presented in various publications (e.g. [16, 19, 20]). According to these similar concepts, the elements can be grouped into the levels single processes, process chains, technical building services, and the building shell. Another way of structuring manufacturing systems is proposed by introducing the levels micro, meso and macro [21], whereas macro refers to the whole factory, meso to groups of elements such as process chains and micro to single machines, processes and individual work pieces. Derived from these concepts was the framework for multi-level modeling and simulation that structures model types for relevant manufacturing system elements and shows interfaces as well as relevant variables for data exchange (see Figure 5).

The micro level contains models of processes and machines. Machines perform processes and have different states (e.g. idle, processing). A related process model provides for example the calculated processing time. The meso level contains the process chain model as well as product models describing the characteristics and required processes for each product type. The process chain model receives the energy consumptions for different states, the TBS demands and other relevant parameters (e.g. heat emissions) from machine models. This information is used to calculate the load profiles and energy demands for the entire process chain as well as the embodied energy per product, which can be written to the product model. Process models can send information about the product properties to the product model. The macro level contains the models for TBS equipment such as compressed air generation or coolant supply as well as the building model representing the factory building shell and different zones within the building. The process chain model exchanges data with TBS models such as demand and supply as well as energy demands.

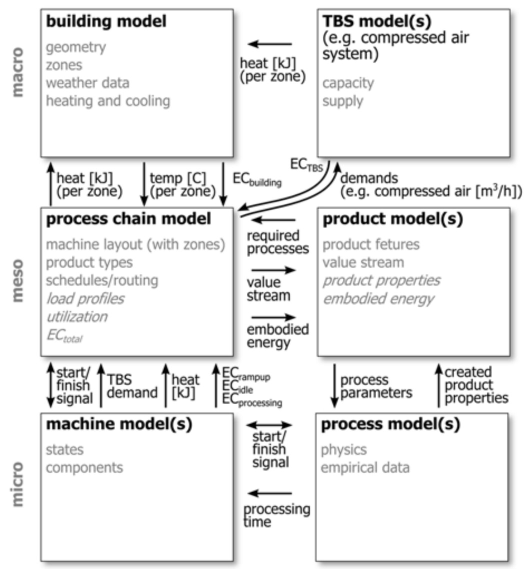

Fig. 5. Framework for multi-level modeling and simulation

Furthermore, the process chain model provides the aggregated heat emissions from the machines (e.g. ovens) to the building model which in turn sends the temperature for each zone and the energy demand of the building equipment (e.g. heating and cooling units).

This framework includes all relevant models needed for creating a holistic manufacturing model for predicting the energy demands from the production of a specific component. These models can be realized in specific software tools or integrated within larger models. For example, machine models representing different states could be integrated within a process chain model. Finally it should be noted that it is not necessary to create all described models but the framework also can provide guidance about how to combine only few specific models. The next section gives an example of combining a process chain model with a process model.

4. Application

The concept of multi-level modeling and simulation is exemplarily applied to the manufacturing of two different semi-finished products. The study serves as decision support, if either an aluminum sheet (Part 1) or an organic sheet (CFRP preform, Part 2) is more appropriate as basis for a hybrid component. Both sheets have a size of 500 mm x 800 mm and are deep-drawn by 150 mm. Part 1 has a thickness of 2 mm and Part 2 of 1 mm.

Main comparison criteria are the energy demands of the manufacturing processes and the lead time. Both sheets pass through a similar process chain from cutting (machining center), over forming (hydraulic press), to drilling. The differences between the two parts are the following: Part 1 requires higher forming pressures and cutting forces which also result in longer process times. Part 2 requires an additional heating process prior to forming. The two process chains are illustrated in Figure 6.

The energy demands and lead times should be evaluated in a multi-level process chain model which combines existing process models with a superordinate material flow simulation. The next sub-sections exemplarily describe the process chain model, the forming process model, and simulation results.

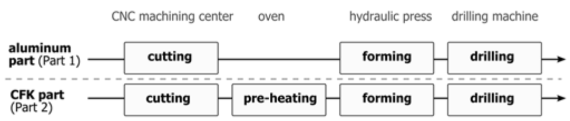

Fig. 6. Process chain of both parts under survey

4.1. Process chain simulation model

According to the framework for multi-level modeling, the process chain model has to represent the required process sequence for both product types and it has to exchange start and stop signals with machine models. Since different hybrid lightweight parts may have a different set of processes, the flow of products through the available machines has to be flexible in order to simulate different products/jobs at the same time. The simulation model is realized within the software AnyLogic® which is a hybrid simulation environment allowing to combine discrete event, dynamic systems and agent based simulation. In the process chain model, machines can be placed on a virtual shop floor and the routing can be defined for products or jobs. Figure 7 shows a screenshot of the process chain of Part 2 which consists of four machines. The grey boxes represent the parts in progress.

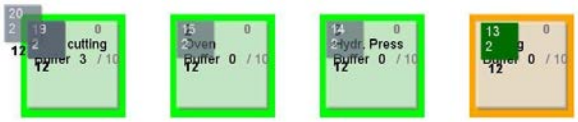

Fig. 7. Screenshot: Process chain model with four machines

The parts are individual objects (agents) which travel from machine to machine. The times of the movements are adjustable as they present the logistic processes as well as the setup times. The machines are also modeled as objects which have their individual behavior and states. In AnyLogic®, elements from the enterprise library are used for modeling the product flow through the machine and a state chart is used for representing operational states such as off, ramp-up, idle and processing. Figure 8 shows a simplified generic machine model. These models do not represent the components of a machine or the physical effects during processing. These aspects are modeled within separate process models.

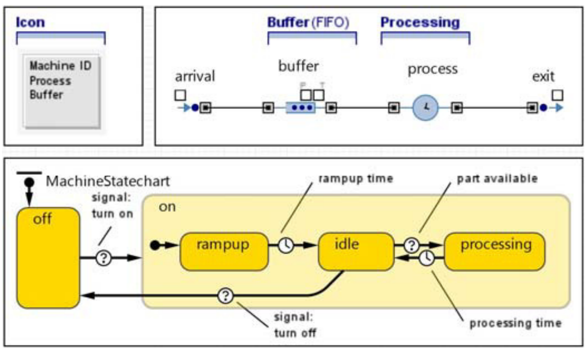

Fig. 8. Machine object model: Top: Enterprise library elements for buffering and processing of product entities; Bottom: Operational states of the machine.

4.2. Process model for forming process

As an example, presented is a model for a forming process using a hydraulic press. Large hydraulic presses are often employed for forming metal sheets and organic sheets. To predict the energy demand for the forming processes of different machine types and products, a parameter-based consumption model has been developed in MATLAB®/Simulink®. This model can be configured according to real press specification sand calculate the resulting energy demands. Figure 9 shows the model's in- and outputs as well as the most relevant components and energy flows according to [22].

The model has originally been developed for the purpose of dimensioning a new hydraulic press to be purchased. In a bottom-up approach, modeled were the consumption behaviors of the major components of a typical hydraulic press based on physical effects and aggregated on a system level. Apart from its original purpose, this model can also be employed for the derivation of improvement potentials regarding energy demand because it reflects the influencing parameters, their interactions, and the main consumers. Moreover, it can be utilized to calculate the specific energy input into one part which is an important factor for product life cycle assessments. In this study, the model is parameterized to depict the behavior of a 25,000 kN press with a maximum output of 0.8 MW

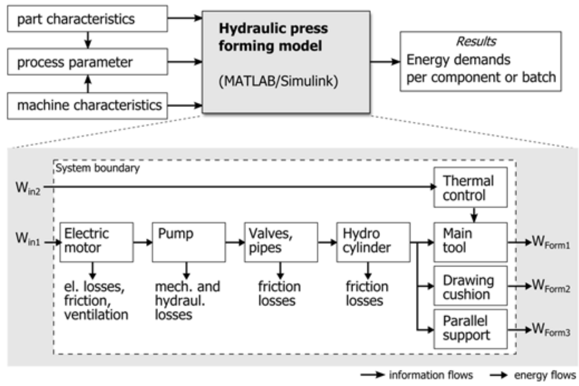

Fig. 9. In- and outputs of press model as well as model components and energy flows according to [22].

4.3. Coupled modeling approach

For this case study, the hydraulic press model was coupled with the process chain model. This is achieved by transferring the MATLAB® model to a java file which can be executed by AnyLogic®. AnyLogic® sets the product and machine specific parameters to the MATLAB® model, pauses the simulation, and receives the results when the calculation is finished.

4.4. Simulation results

For each part type, simulated was the manufacturing of a batch of 50 parts. All machines were turned on at the beginning of the simulation run and stayed on until the batch was finished. The buffer size of each machine is assumed to be ten. During a simulation run, the electrical load profiles and the resulting energy demands are determined for all machines. The indirect energy demands (e.g. for compressed air) are neglected so far. Figure 10 presents the results of two simulation runs for Part 1 and Part 2 respectively. The Figure reveals that the power demand in average is much higher for Part 1 compared to Part 2. Also the peak loads during the manufacturing of Part 1 are three times as high (660 kW compared to 220 kW). The peaks are in both cases caused by the hydraulic press. In direct comparison to the forming process, all other processes could almost be neglected.

The causes for these high overall power demands are the required pressures for the forming operation. Part 2 is preheated and thus requires a significantly lower pressure.

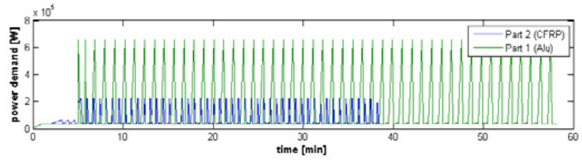

Fig. 10. Results: Power load profiles for both batches for Part 1 and 2.

The total energy consumption of the manufacturing of the batch of Part 1 is 92.73 kWh and almost twice as high as for Part 2 (48.73 kWh). This can be explained by the higher power demands but also by the longer lead time. The longer processing time for the cutting of aluminum results in a longer required tact time. This reduces the utilization of the following processes and causes higher energy demands during machine idle states and longer waiting times of parts in buffers. As a result, the lead time of Part 1 is longer compared to Part 2 (58.87 and 39.45 min). Table 1 summarizes the results.

Table 1. Exemplary results of simulation runs

Key performance indicators	Part 1 (alu)	Part 2 (CFRP)
Lead time of 100 parts [min]	58.87	39.45
Energy demand of processes [kWh]	92.73	48.83
Peak load [kW]	660	220

From a theoretical perspective, in this case the manufacturing of Part 2 is relatively less energy intensive and requires less time. These results, however, depend on the assumptions regarding process and machine parameters, the processing times and the forming process model.

5. Conclusion and outlook

The comprehensive framework for multi-level modeling and simulation of manufacturing systems has been applied to a specific modeling case. Existing models of different disciplines realized in AnyLogic® (process chain) and MATLAB® (single process) have successfully been coupled to compare the environmental impacts of two product design alternatives. It was exemplarily shown for the manufacturing domain how combined models can be used in order to predict performance indicators. However, the results rely on various assumptions and should be understood as a demonstration of possible applications. An important next task is the validation of the process models using real machines and product designs. Furthermore, the developed models will be used for testing the sensitivity of parameters as well as different process chain configurations (e.g. buffer sizes).

The developed concept provides the foundation for a comprehensive consideration of all relevant product life cycle data from material flow in production to energy and resource demand in the product design phase. In the future, the multi-level modeling approach can be employed to integrate even more expert-specific models in order to create a holistic understanding of the linkage between product design characteristics and environmental impacts. For example, of huge interest is the connection of the multi-level simulation approach with models of the automobile use phase and end of life recycling process models.

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