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REGULAR PAPER

Integration of Energy Oriented Manufacturing Simulation into the Life Cycle Evaluation of Lightweight Body Parts

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Abstract

Recent years introduced process and material innovations in the design and manufacturing of lightweight body parts for larger scale manufacturing. However, lightweight materials and new manufacturing technologies often carry a higher environmental burden in earlier life cycle stages. The prospective life cycle evaluation of lightweight body parts remains to this day a challenging task. Yet, a functioning evaluation approach in early design stages is the prerequisite for integrating assessment results in engineering processes and thus allowing for a life cycle oriented decision making. The current paper aims to contribute to the goal of a prospective life cycle evaluation of fiber-reinforced lightweight body parts by improving models that enable to predict energy and material flows in the manufacturing stage. To this end, a modeling and simulation approach has been developed that integrates bottom-up process models into a process chain model. The approach is exemplarily applied on a case study of a door concept. In particular, the energy intensity of compression molding of glass fiber and carbon fiber sheet molding compounds has been analyzed and compared over the life cycle with a steel reference part.

Keywords Lightweight body parts · Life cycle evaluation · Energy oriented manufacturing simulation · Sheet molding compound · Compression molding

List of Symbols

A	Surface area
b	Breadth of the body part
B	Breadth of the design space
c	Specific heat capacity
d	Thickness of mold insulation
g	Gravitational force equivalent
h	Heat transfer coefficient
H	Height of the design space
k	Thermal conductivity
m	Weight
p	Pressure
$\dot{Q}$	Heat flow rate
s	Sheet thickness
t	Time
T	Temperature
v	Speed

Greek Symbols

ε	Emissivity
η	Energy conversion efficiency
σ	Stefan–Boltzmann constant
ψ	Fiber mass ratio

1 Introduction and Background

Fiber reinforced plastics (FRP) are progressively employed in vehicle body structures either in addition to conventional steel structures in so-called multi-material designs or as a replacement for steel-based designs. While FRP do help to reduce vehicle weight, hence reduce environmental impacts during the use stage of those vehicles, they tend to create a higher environmental burden during material production and parts manufacturing [1, 2]. In the sense of a holistic life cycle engineering, additional environmental burdens from one life cycle stage should be at least compensated by other life cycle stages [1, 3]. Figure 1 qualitatively shows the environmental

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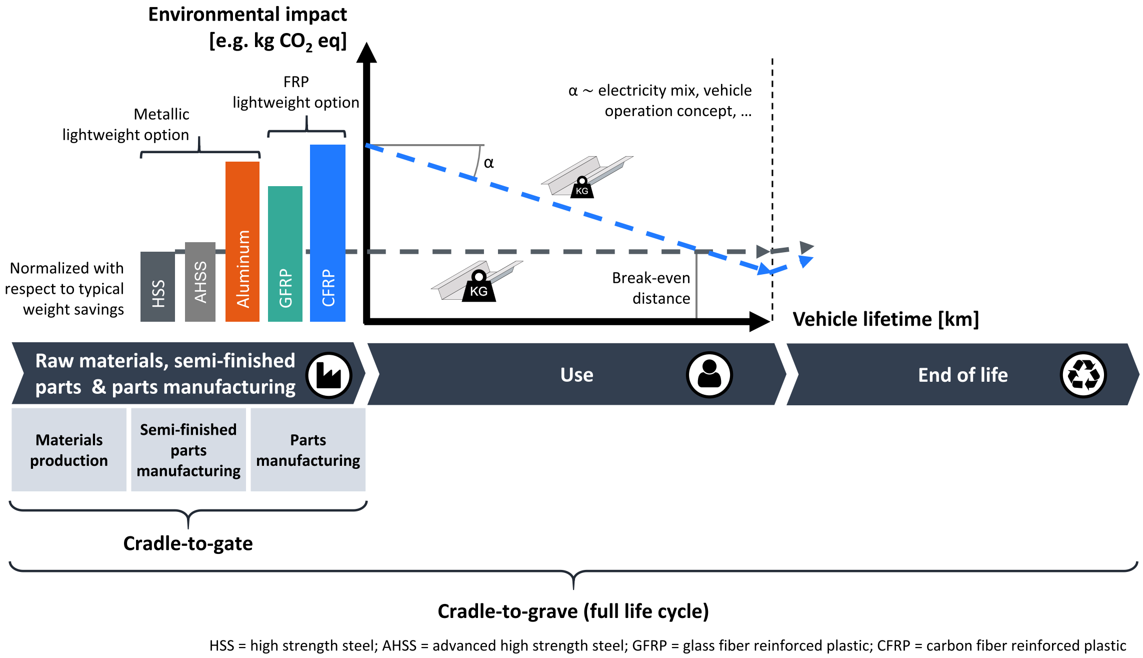


Fig. 1 Environmental break-even for lightweight body part concepts in relation to conventional designs in electric vehicles (qualitative representation, inspired by [4])

impacts of lightweight FRP and metallic parts alongside an electric vehicle´s life cycle compared to a reference part. Weight reductions induce energy savings during the use stage, which lead to a falling curve of the lightweight part in comparison to the reference part [4]. Thereby, the benefit of lightweighting increases in scenarios with comparably high environmental impacts from energy provision, e.g. due to a high share of fossil energy carriers [5]. Manufacturing processes for FRP-based lightweight parts might show a lower energy and resource efficiency compared to steel processing due to their potential lower technical maturity and additional processing steps in the process chain. The high embodied energy of lightweight materials increases the pressure for a high material efficiency throughout manufacturing. Cut-offs and their processing represent a major contribution factor to environmental impacts due to their embodied energy from materials production [6]. Similar observations are made for end-of-life processing [7]. Conventional body parts undergo established end-of-life treatments with secondary materials made available to material markets. Lightweight body parts, especially multi-material designs, are likely to lead to lower recovery rates [8].

Due to the different influence factors on the life cycle environmental impacts of FRP lightweight body parts, their benefits or drawbacks in comparison to reference designs remain ambiguous in early stage product and production planning. Therefore, this evaluation should be a prospective task in those stages [9, 10]. The current paper aims to contribute to that goal by improving models that enable to predict energy and material flows in the manufacturing stage. While Sect. 1.1 further elaborates the challenges to do so, Sect. 1.2 presents and compares methodological approaches from the state of research that could serve as a basis. Section 1.3 summarizes the Goal & Scope of the research paper.

1.1 Challenges in Evaluating Environmental Impacts of Manufacturing FRP-Based Lightweight Body Parts

FRP-based body parts exploit their full lightweight potential in load-path optimized structures, which calls for the development of new manufacturing processes that fulfil the requirements of high-volume production [11]. Figure 2 illustrates a non-comprehensive overview of FRP-based process chains suitable for manufacturing automotive structural body parts. The manufacturing of FRP parts is performed in multi-stage process chains. The first stage is materials production of the reinforcing glass or carbon fibers and thermoplastic or thermoset resin as matrix materials. Materials production is followed by processing them to semi-finished parts and finally by parts manufacturing. Depending on the matrix material, fiber type and product geometry, different manufacturing process routes are taken [12, 13].

In general, the quantitative evaluation of environmental impacts of technical processes and products can be performed following the Life Cycle Assessment (LCA) methodology. LCA thereby relies on a detailed description of energy and material flows of the observed system, the so-called Life

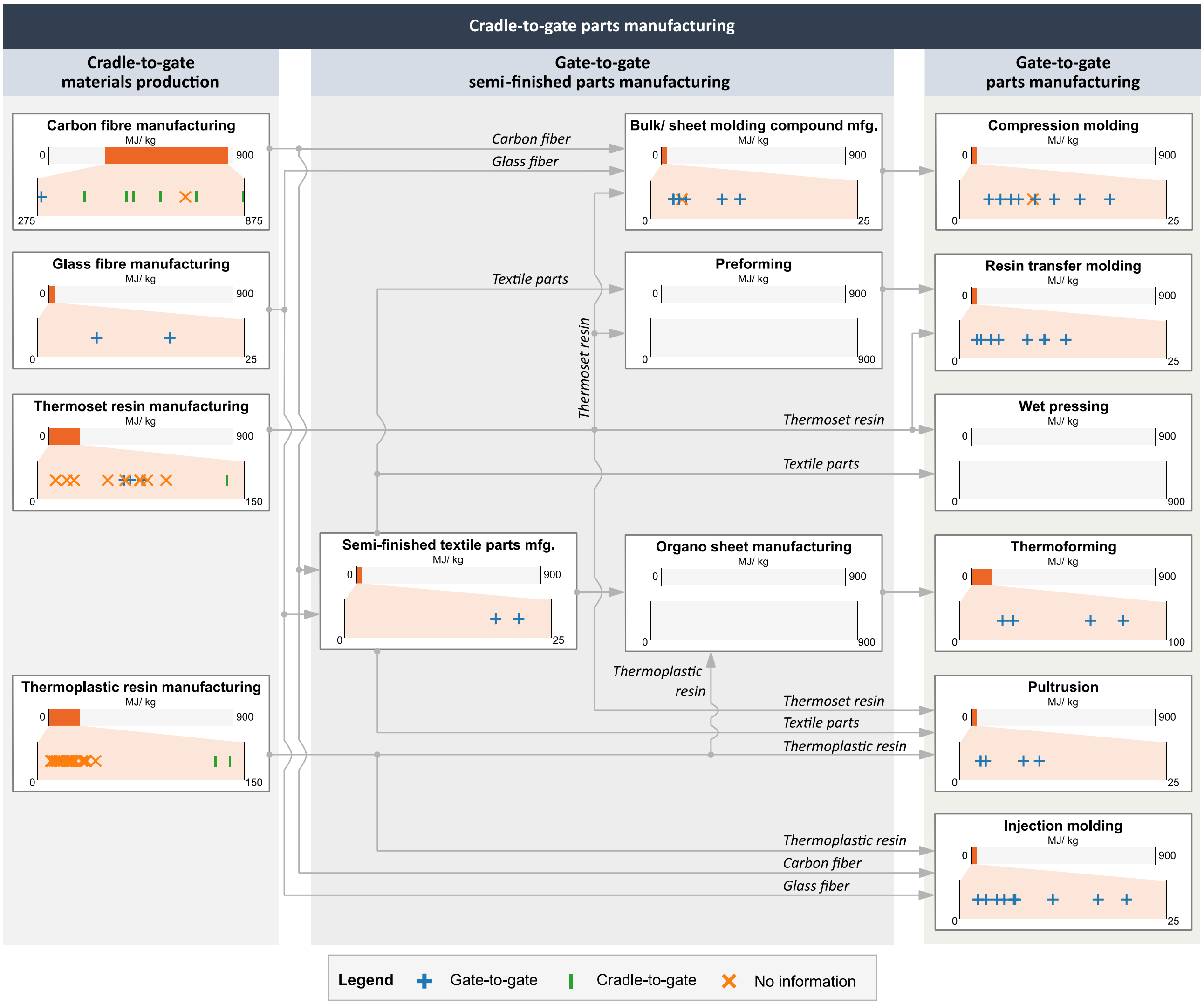


Fig. 2 Overview of reported energy demands in FRP-based manufacturing process routes for automotive structural lightweight body parts (process routes adapted from [12], list of references for energy demands in supplementary material Table A1)

Cycle Inventory (LCI). Information on energy and material demands of technical processes needs to be obtained and linked back to part-specific energy and material intensities that form the LCI model [1]. Energy and material data can either rely on empirical data, prospectively oriented engineering models, e.g. simulation studies, or a combination of both [14].

To display the availability on relevant LCI data in manufacturing FRP body parts, Fig. 2 further illustrates energy intensities of the corresponding FRP materials and manufacturing processes as reported in literature. The figure displays more than 100 data points and the corresponding life cycle perspective encompassing the whole process chain starting from materials production over semi-finished parts manufacturing and final parts manufacturing. As the energy intensities are often reported in different measurement units, the values in Fig. 2 were converted to MJ/kg. The purpose of the figure is to highlight data gaps, missing information on assessment methodologies of reported energy demands and quantitative ranges per material or manufacturing step. Limitations occur both for FRP materials and their manufacturing processes [6]. Taking the cradle-to-gate production of fibers and matrix materials as an example, existing data only allows an aggregated view on the energy demands while information on the properties of the materials itself, system boundaries for assessment and production scales are often ambiguous or not known [15]. Despite those shortcomings, Fig. 2 illustrates the dominance of the cradle-to-gate fiber and matrix production over subsequent manufacturing processes on the cradle-to-gate energy intensity of FRP parts.

With respect to gate-to-gate parts processes, Fig. 2 shows that several publications investigate energy intensities for

FRP semi-finished and final parts manufacturing. However, only few publications report primary data, other studies make a recourse to these. As an example, the energy intensities reported by Suzuki et al. [16] serve as a data reference in various following contributions of other authors, e.g. in [17–20]. Despite primary data collection, absolute values are not always reported. For example, Hohmann et al. conducted extensive measurement campaigns and a parametric study with different process parameters on a process chain for manufacturing parts from carbon fiber reinforced plastics (CFRP), but did not present absolute energy intensities [6, 21].

Altogether, a research demand to improve information on determining energy demands for manufacturing of FRP body parts becomes apparent. Data gaps and inconsistencies are omnipresent across the whole process chain and studies often only provide incomplete information about the investigated products and differ in their scope. Furthermore, the reported energy intensities do not fully cover the processes and process chains. Preforming, organo sheet manufacturing and wet pressing are examples, where no empirical values could be identified. As described before, material intensity as well plays a crucial role in assessing environmental impacts of manufacturing processes of FRP parts. However, the assessed studies do not provide information on cut-offs or recycling rates. Therefore, LCI models built on that basis tend to be incomplete and thus lack comparability to the well-studied processes for manufacturing conventional steel designs.

1.2 Concepts and Approaches for Estimating the Environmental Impact of Manufacturing Processes Via Modeling and Simulation

The role of manufacturing towards sustainability has already been discussed in previous publications, e.g. [22, 23]. Within the state of research, there are several methodological approaches to determine the energy demand of manufacturing unit processes. In order to support the collection of reliable LCI data of unit processes, Kellens et al. suggest an in-depth analysis that includes a time, power, consumables and emissions study [24]. The methodology distinguishes between different machine states (e.g. standby and processing mode) and allocates state-based energy, consumables and emissions data. The methodology suggests the measurement or estimation of related data if none available. Duflou et al. compare the methods of theoretical calculations, simple screening approaches and detailed in-depth analysis [25]. The results indicate high discrepancies between the energy demands but also regarding the efforts to conduct an analysis [25]. The characterization of the energy demand based on empirical models has been investigated for different manufacturing processes, e.g. in [26–30]. Schmidt et al. developed a methodology for the prediction of energy demands of generic machine tools types [31]. The approach is based on energy measurements and a calculation logic based on the machine´s electrical load profile [31]. While measuring and analyzing energy demands lies at hand, it is not straightforward in the case of new and currently developed manufacturing processes for lightweight body parts. Data acquisition availability is strongly limited in early development phases and when available, often refers to small-scale processes. In contrast to that, LCI-data for the life cycle evaluation of lightweight body parts needs to represent large-scale production.

Taking the limited data availability into account, different methodological approaches are needed that are able to predict energy demands of production processes. Modeling and simulation of manufacturing systems on different levels (process, machine and process chain) has been widely applied in the domain of energy efficiency and production planning [32]. Examples for the application of a modeling and simulation methodology to perform a LCA of a manufacturing system can also be found [33]. As an example, Löfgren et al. and Rödger et al. use simulation results as a data source for a subsequent LCA [34, 35]. These works relate manufacturing system configurations and production strategies with their corresponding environmental impact. However, previous methodological approaches and applications of modeling and simulation within an LCA still show some incoherence [33]. Since many alternatives exist regarding system boundaries in simulation studies of manufacturing systems, Seow et al. introduced a framework for modeling energy flows from the product perspective [36, 37]. The framework differentiates between the direct and indirect energy demand that together add up to the product´s embodied energy. While the direct energy demand is understood as the energy required to manufacture a product (e.g. machining, forming), the indirect energy is required to maintain required conditions in a production environment (e.g. heating, ventilation and lighting) [36, 37]. Lee et al. presented a physics-based modelling approach for energy usage profiling of machine tools [38]. The emphasis of the approach lies on detailed modeling the feed drive based on process parameters and the control program, but also other machine tool components are integrated with simplified models in a virtual machine tool [38]. Schrems developed a simulation approach to predict the electrical energy demand of production machines [39]. To this end, a machine tool, an industrial parts washer and a furnace was modeled. The approach breaks down machines on their energy relevant functional components. The energy demands are calculated based on physical equations. Abele et al. extended this approach for machine tools by predicting the machine tools electrical energy profile based on process parameters and numerical control program [40]. These modeling approaches are intended to increase the energy efficiency of machine tools, as a planning support during procurement and energy-aware production planning. Their strength with respect to new manufacturing processes is that they can be applied independently from electrical measurements [41]. Herrmann et al. and Thiede introduced a flexible modeling approach for process chains including the technical building services (TBS) perspective [42, 43]. The process chain model considers all relevant energy flows of factory systems and respects their dynamics with state based energy demands [42, 43]. An up-to-date application of energy oriented process chain modeling and simulation is presented on the case of plating process chains in [44]. Schönemann et al. developed a holistic multiscale simulation approach for production systems [45]. The heart of the modeling approach is a process chain core model that controls the product flow and connects lower system elements (machines and processes) with higher system elements (TBS and building structure) [45].

In the context of lightweight body parts, Schönemann et al. applied a multi-level modeling approach for the estimation of LCI data for multi-material components [46]. The approach intends to integrate decoupled machine and process models in a generic process chain model. In order to overcome data availability issues, the modeling of energy demands is suggested based on mathematical and physical models [46]. Hürkamp et al. propose a modeling and simulation framework for the integration of different computational methods from product and production planning of lightweight body parts [47]. According to the framework, finite element analyses of products and of their related production process provide process parameters for energy-oriented machine and process chain models [47].

Table 1 summarizes the research contributions regarding their goals, scope, addressed production system levels and means of model parametrization. The table shows that there are several valuable examples for energy oriented modeling and simulation of manufacturing systems on different levels. The focus of these contributions lies rather on the production planning and operation (e.g. supporting purchasing decisions, evaluating optimization measures, increasing energy efficiency or highlighting goal conflicts between operation strategies) than on the prospective life cycle evaluation of products or manufacturing processes. Some contributions explicitly target the integration of manufacturing system simulation into the LCA procedure. However, they rely at the same time on empirical data for model parametrization. In conclusion, several single aspects are addressed by different contributions but none fully addresses the prospective

Table 1 Overview of concepts and approaches for estimating the environmental impact of manufacturing processes via modeling and simulation

		Löfgren et al. 2011	Herrmann et al. 2011 & Thiede 2012	Seow et al. 2011 & Seow et al. 2013	Lee et al. 2014	Schrems 2014	Abele et al. 2015	Schönemann et al. 2016	Schönemann et al. 2019	Hürkamp et al. 2020	Rödger et al. 2020
Goal/ target use case	Production planning & operation	▨	■	■	■	■	■	■	■	■	▨
	Life cycle evaluation	■	▨	▨	□	□	□	▨	▨	□	■
Scope	Energy intensity	■	■	■	■	■	■	■	■	■	■
	Material intensity	▨	□	□	□	□	□	□	□	□	□
	Product parameters	▨	□	▨	▨	□	■	■	■	■	□
Production system levels	Process	□	□	□	■	■	■	■	■	■	□
	Machine	■	■	■	▨	■	■	■	■	■	■
	Process chain	■	■	■	□	■	□	■	■	■	■
Model parametrization	Empirical	■	■	■	▨	□	□	□	■	□	■
	Physics-based	□	□	▨	■	■	■	▨	□	■	□

□ not covered ▨ partly covered ■ fully covered life cycle evaluation of manufacturing process chains that is required for the current setting of FRP-based lightweight body parts.

1.3 Goals and Scope of the Paper

Against the aforementioned challenges, this paper pursues a model-based life cycle engineering approach that enables to derive quantitative information on energy and material intensities for manufacturing FRP parts at early phases of product development and production planning. As the availability of empirical energy data for FRP manufacturing processes is limited, a physics-based modeling and simulation approach is proposed. This will be used to estimate the energy demands of new manufacturing processes on machine and respective machine component level. Also, inherent dynamics of process chains, e.g. waiting for parts and quality issues by error propagation, play a crucial role in the total energy intensity of manufacturing process chains and should therefore be considered. Due to the high embodied energies of lightweight materials, also potential material losses are of interest on the process chain level. In order to link back the results to influences in product development and production planning, the model should be able to single out relevant contributing factors. Well-known that the modeling approach only delivers estimations and limitations exist, the question is, where the environmental hotspots are and what the range of environmental impacts is. Therefore, the physics-based models for final parts manufacturing is combined with static models of semi-finished parts and final parts manufacturing. On this basis, a parametric study to assess model sensitivities can be performed. The developed approach is demonstrated on a case study from the automotive industry.

2 Approach for the Estimation of Environmental Impacts of New Manufacturing Processes in the Context of Lightweight Body Parts

2.1 General Concept

In light of the aforementioned challenges, a model based concept is suggested to enable the estimation of environmental impacts of manufacturing processes for lightweight body parts. As argued by Schönemann et al., production system simulation has proven to be an appropriate method to evaluate and analyze potential problem shifting and dynamic interrelationships within manufacturing systems. It is a favored method, where empirical data is scarce, the studied system is complex and includes dynamic characteristics between manufacturing system elements [45]. Manufacturing systems for lightweight body parts that incorporate new manufacturing processes fulfill these criteria (see Sect. 1.1 and Fig. 2). Therefore, a modeling and simulation approach combined with a scenario analysis and parametric study is proposed (see Fig. 3). The backbone of the concept is the process chain model, which represents the parts manufacturing life cycle stage of lightweight body concepts. The process chain model interlinks the material flow with energy-oriented machine models and buffers that together calculate the energy and material demand. The process chain is modeled in a simulation software environment. Upstream processes (materials production and semi-finished parts manufacturing), which are not represented by the process chain model, are modeled in a LCA software environment. The LCA model integrates the energy and material demands of the process chain model. Thus, it extends its scope from a gate-to-gate to a cradle-to-gate perspective. Furthermore, the LCA representation of the whole process chain is split in the foreground and the background system. While the foreground system includes the manufacturing processes themselves, the background system includes the energy system. The differentiation between the two systems allows for taking into account technological, spatial and temporal aspects in a scenario analysis and parametric study.

2.2 Gate-to-Gate Modeling

Focusing on the gate-to-gate perspective the purpose of the process chain model is the provision of the energy and material intensity of lightweight body part manufacturing for a subsequent life cycle evaluation. A multi-layer modeling approach is proposed for modeling the energy and material flows with an appropriate level of detail. Figure 4 presents the layers and the modeling logic associated with each level. The system boundary includes production machines and manufacturing process chains. At the current development stage of the modeling approach, energy demands from technical building services exceed the scope of the model. However, as the TBS is a large contributor to the total energy demand of a manufacturing facility, where accessible, historical TBS energy demand data should be a substitute for modeled TBS energy demands. A further simplification is the only focus on electrical energy flows. Other types of energy carriers are neglected at the current stage of model development.

The product level represents the starting point for the analysis and an interface for the life cycle evaluation. A processing sequence is derived based on product specifications. This serves as an input for the process chain modeling. Deriving the processing sequence can be facilitated with the help of Fig. 2, if the product designer has not already defined it. The figure acts as a simple guide for the identification of suitable manufacturing process

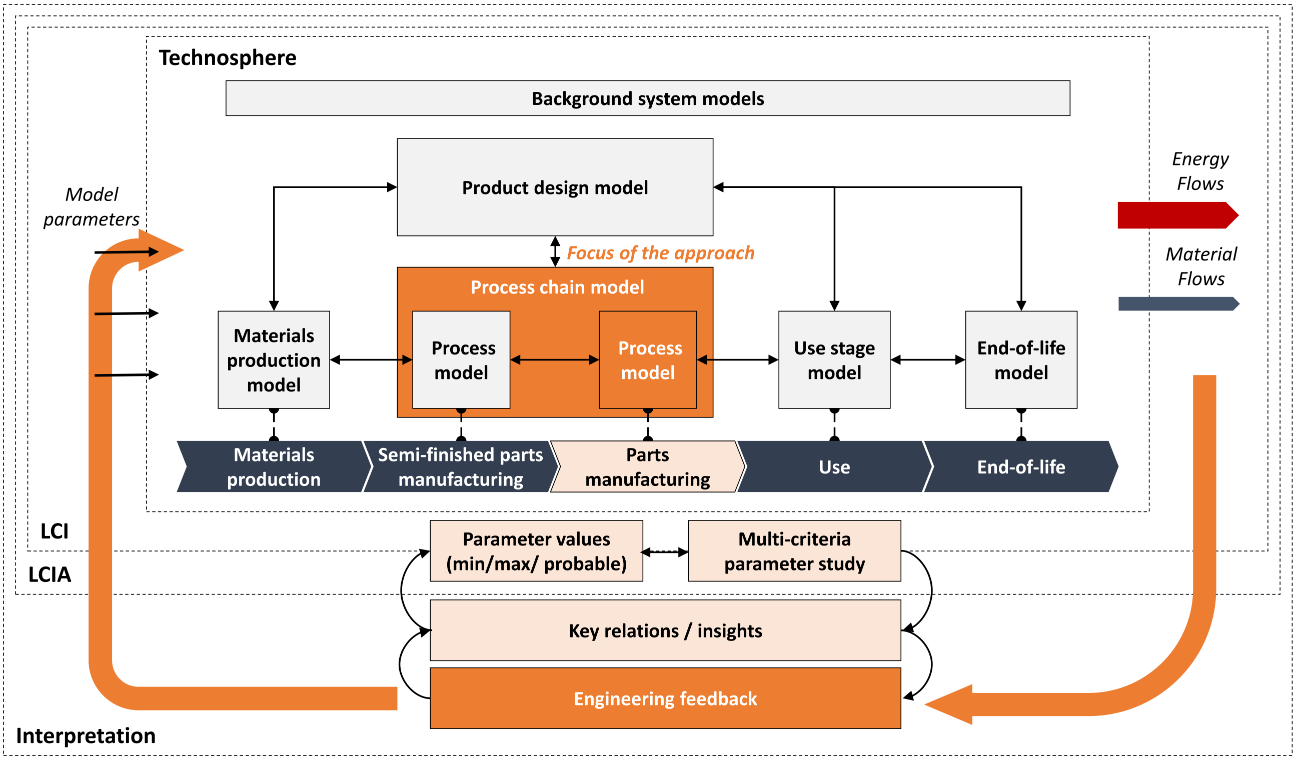
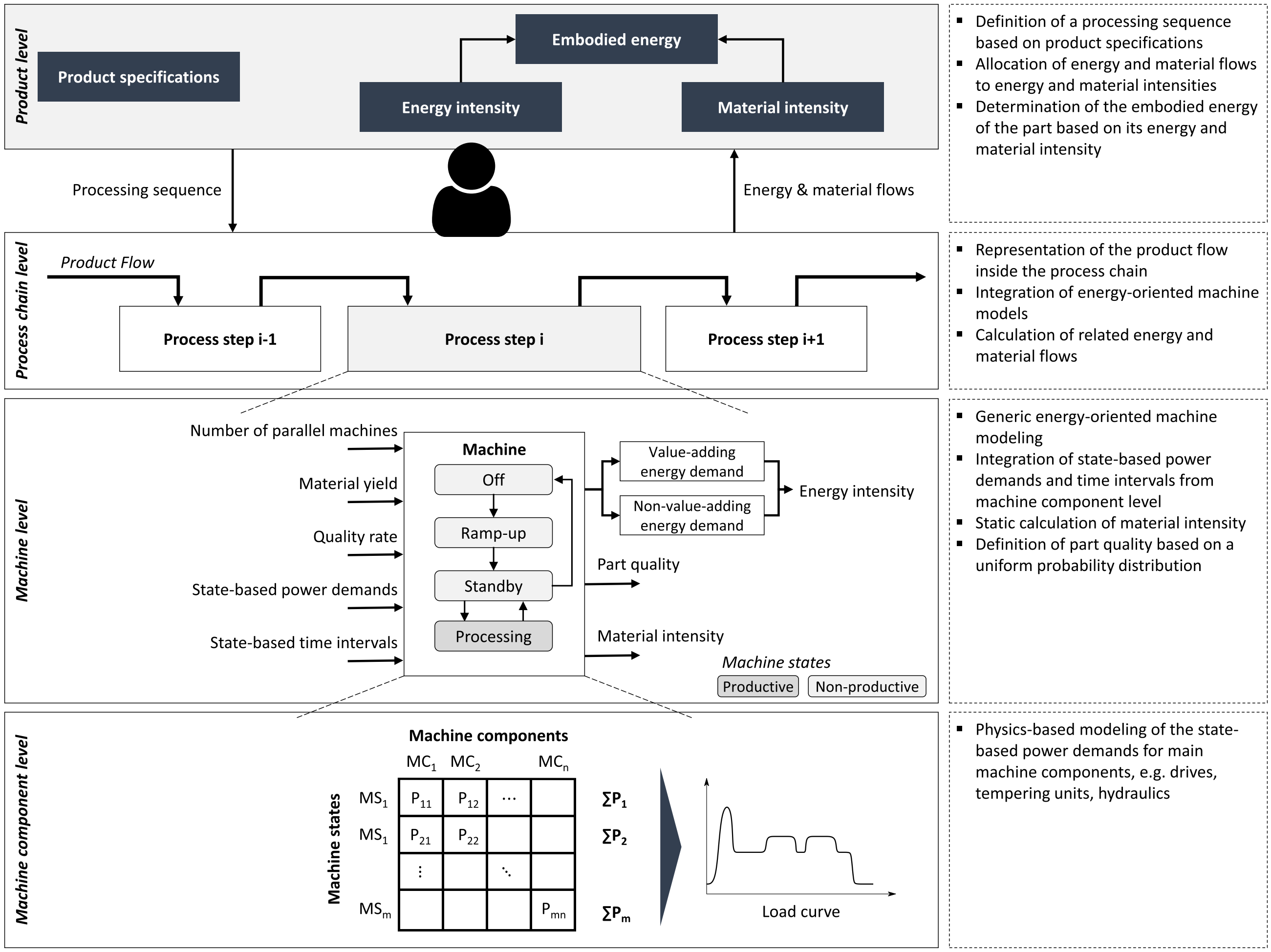


Fig. 3 Model based estimation of environmental impacts of new manufacturing processes in the context of lightweight body parts (focus highlighted in orange)

routes based on basic product specifications. To this end, different manufacturing process chains are illustrated for thermoset and thermoplastic matrix materials as well as carbon and glass fibers. All illustrated manufacturing processes are suitable for high production volumes. The product level further serves as an interface between the gate-to-gate modeling and the life cycle evaluation. For this purpose, energy and material flows from the process chain model are aggregated and allocated to the energy and material intensity of the analyzed body part. The aggregation of energy flows differentiates between the value-adding and non-value adding energy demand. Both value-adding and non-value-adding energy demands are summed up over all process steps. Together they form the product´s energy intensity. In this modeling approach, the value-adding energy demand indicates the energy demand from productive machine states. In contrast, the non-value-adding energy demand comprises unproductive machine states. The energy demand for a reject part during productive machine states is considered as non-value adding energy. Therefore, it is equally allocated to the non-value-adding energy demand of good parts. Both, the energy intensity and the material intensity can be accumulated to the embodied energy of the part. This indicator simultaneously integrates both perspectives, the energy demand from parts manufacturing and the impact of quality rates and material yield of the process chain.

The process chain model represents the product flow between the previously chosen manufacturing processes and buffers. Instead of modeling a specific process chain, a generic process chain model was developed. This can be flexibly adapted to the prevailing conditions of a specific case within a case study. The process chain level is closely connected to the machine level, as the concept proposes the combination of energy-oriented bottom-up machine models in the process chain model. Therefore, besides the product flow (that emerges from the processing sequence, the number of parallel machines in each process step and the corresponding processing times), the process chain model integrates energy flows from the machine models. This goes beyond a simple total of the energy intensities of isolated machine models. While isolated machine models do calculate the value-adding energy demand of one product, they neglect non-value adding energy demands for waiting times, machine ramp-ups and rejects parts. Taking in a process chain perspective allows for considering these dynamic interrelationships. Therefore, machine-state-based energy flows (e.g. waiting for parts and producing) are integrated in the process chain model. Having the purpose of this modeling approach in mind, some limitations have been made. In



MS = machine component; MS = machine state; n = number of machine components; m = number of machine states; i,j = indices

Fig. 4 Estimation of energy and material intensity of manufacturing processes in a gate-to-gate perspective

order to handle modeling complexity on process chain level, the spatial positioning on shop floor and the failure behavior of machines have been neglected.

The model logic on machine level also represents a generic energy-oriented machine model. The model emulates a generic machine behavior by differentiating between four distinct machine states (off, ramp-up, standby and processing). Each state is parametrized by an own power demand and transition times for ramping up and processing a part are defined. The remaining transitions are controlled by the product flow on process chain level (e.g. switching from standby to processing at product arrival). Material cut-offs and other material waste are calculated only in a static manner. They are assumed to be manufacturing process and part geometry specific. The second factor influencing the material intensity is the quality rate of the machine, which defines part quality. The quality rate is defined by a probability function. In the simplest case, this is a uniform probability distribution. If further knowledge is available, custom probability distributions can also be applied. The generic machine models can either be parametrized with empirical data (following a measurement campaign) or with estimated state-based power demands (as described on the machine component level).

The machine component level is employed optionally. This level provides an estimation of state-based electricity power demands of a machine, when empirical data is not accessible. In order to handle the complexity at the current development stage of the methodology, further energy carriers are neglected. However, to fully represent the energy flows on machine component level, further energy carriers (e.g. compressed air) should also be modeled. The idea is to break down a machine to its main functional components (e.g. drives, tempering units and hydraulic components) and analyze their behavior and power demands. By this means, power demands are calculated for each identified machine component and machine state. It is important to mention that the required detail level regarding the machine states goes beyond the four states from the generic machine model. Instead, manufacturing process-specific states need to be identified. In particular, the processing state needs to be further broken down into further sub-states. The power demands of each machine component superpose and compose together the machine´s electrical load curve. The power demands are approximated using physical laws and a set of assumptions regarding machine and process parameters. Also, product specifications from the product level provide valuable input for the calculations (e.g. mass, specific heat capacity, geometry, etc.). The estimation follows a backward logic: first defining the energy required for the production process itself and secondly calculating power demand by considering the efficiency of machine components. Due to a large variety of manufacturing processes for lightweight body parts, diversity of related manufacturing equipment and interrelationships between product, process and machine parameters and the resulting power demands, the modeling process at this level is time consuming and requires expert knowledge.

3 Case Study

In the following, the application of the presented approach will be demonstrated on a case study from the automotive industry. Its objective is to analyze the greenhouse gas emissions reduction potential of different door concepts in the life cycle of an electrically powered vehicle.

3.1 Definition of the Design Concepts

The case study focuses on a door shell concept of a self-driving battery electric vehicle, which is shown in Fig. 5. The outer and inner parts of a vehicle are designed primarily with regard to structural stiffness-relevant requirements, for example to prevent acoustically perceptible vibrations during driving or a buckling under static and dynamic loads. The door structure can be divided into outer and inner as well as structural parts. In the following, the outer part of the door will be examined, which represents the functional unit for the life cycle evaluation. Table 2 summarizes the most important information regarding the design concepts, more information on them can be found in [48]. Next to the steel reference, an aluminum and two FRP concepts are investigated. Weight specifications were retrieved from product designers after proof of concept (i.e. the required mechanical performance is equally fulfilled by all concepts). For the aluminum concept, TL091 T6 is selected as a common material in vehicle applications. Regarding FRP, quasi-isotropic sheet molding compounds (SMC) with a glass and carbon fiber reinforcement are considered. The SMC concepts are of particular interest in the case study due to their cost competitiveness for automotive large-scale series production [49].

The environmental assessment within the case study is performed for four life cycle scenarios, which are described in Table 3. While scenario 1 and 2 describe the life cycle of a vehicle on the European and Chinese market in 2020, scenario 3 and 4 characterize future life cycles in 2030 on the Chinese market. Scenario 3 and 4 consider a theoretical best-case scenario with a closed loop production concept of

Table 2 Definition of the design concepts for the case study

Concept	Weight (kg)	Normalized weight (%)
Steel—CR180BH (reference)	6.5	1.00
Aluminum—TL091 T6	3.2	0.49
GFRP—SMC ($\psi = 0.57$; UP)	3.5	0.54
CFRP—SMC ($\psi = 0.6$; VE)	2.0	0.31

UP unsaturated polyester, *VE* vinyl ester

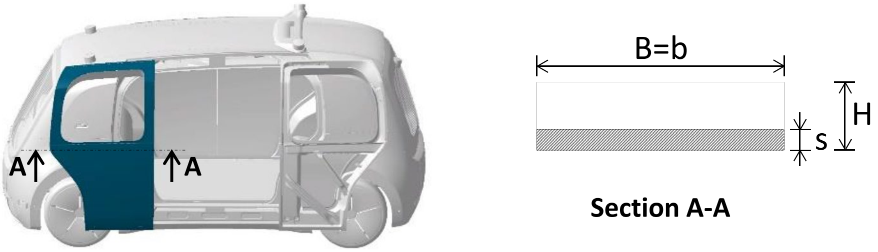


Fig. 5 Definition of the case study

Design concept	**Geometry**	**Design space**	**Design criteria**
Shell design	*b* = 1100 mm	*H* = 5 mm	Bending stiffness
CR180BH	*s* = 0,7 mm	*B* = 1100 mm	
Mass = 6,5 kg			
Material yield = 40 %			

Table 3 Definition of life cycle scenarios for the case study

Scenario specification	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Time horizon	2020	2020	2030	2030
Production site	Germany	China	China, 100% renewable energy in manufacturing	China, 100% renewable energy in manufacturing
Market	Europe	China	China	China
Recovery concept of production scrap	Open loop production	Open loop production	Closed loop production	Closed loop production
Vehicle operation concept	Ownership, 200,000 km	Ownership, 200,000 km	Ownership, 200,000 km	Mobility as a service, 600,000 km

material scrap waste and renewable electricity usage during manufacturing. In addition, a change from vehicle ownership to vehicle usage in a mobility as a service application is evaluated. The difference between the two usage concepts is represented through different mileage. While the ownership usage is estimated with 200,000 km, the mobility as a service vehicle is expected to show a prolonged lifetime of 600,000 km.

3.2 Manufacturing Process Chain

The reference concept is a conventional steel part that can be produced in a regular automotive press shop [50]. State of the art press shops are equipped with mechanical press lines that have a high productivity and are capable for high-volume production [51]. The process chain of the door shell is divided into cutting single pieces from a coil and subsequently forming the door shell in a six-stage processing step [52]. Each forming stage is carried out in the mechanical press line. The process route for the aluminum door concept is identical to the steel reference part [52].

The focus lies in this case study rather on the manufacturing of the door structure with via compression molding of SMC sheets. Compression molding of SMC sheets represents a cost-efficient means for manufacturing A-class automotive fiber-reinforced body parts in high volumes [49]. SMC sheets are fiber-reinforced thermosetting semi-finished products that are supplied uncured to the place of manufacture [53]. Figure 6 depicts the process chain of compression molded SMC sheets with the main process steps. Semi-finished parts manufacturing is decoupled from parts production. Manufacturing of semi-finished SMC sheets is carried out in a continuous process. Chopped glass or carbon fibers are distributed on a layer of matrix material. Afterwards, a second layer of matrix is applied from top. Both sides of the compound sheet are protected by a thin polymeric film. The SMC sandwich is calendared and wound on a roll. In order to mature, the wounded compound sheet rests for several days in a controlled environment. Especially temperature and humidity need to be within defined intervals during this time [53]. The final parts production is a discrete manufacturing process. The compound sheet is cut into pieces and stacked. The carrier film is removed during this process. The stacks are at room temperature when placed in the heated mold. After the mold closes and the pressure and temperature build up, the sheet flows into the cavity and cures afterwards. When curing is finished, the part is demolded. In a subsequent process step, the part is finished

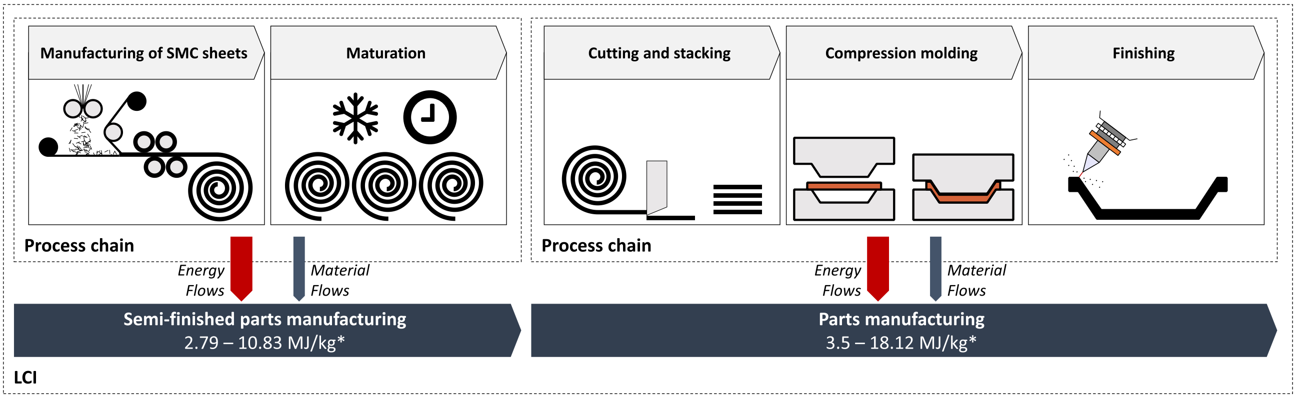


Fig. 6 The process chain of SMC-parts and corresponding energy intensities from literature (*see Table A1 for list of references)

by removing excess material from the sides. In series production, the transfer of the parts between the process steps is automated [49, 53].

3.3 Modeling of the Energy Intensities During Parts Manufacturing

3.3.1 Reference Case and Aluminum Concept

Data acquisition for the steel reference and aluminum concept was carried out on a mechanical press line in a high-volume production stamping plant of an original equipment manufacturer in Germany. Since both design concepts are at a conceptual phase and currently not in production, similar parts from series production have been identified for the energy analysis. The energy intensity was analyzed with the help of the energy management system of the production facility that acquires the aggregated electrical load profile of the press line. The electrical power profiles were analyzed in conjunction with the corresponding production times, which also included changeover, failure and break times. Next to the process related energy demand, the energy demands of the TBS (lighting and air conditioning) were included in the study. To this end, the total TBS energy demand over a period of one year was allocated to one part.

3.3.2 Compression Molding for FRP Concepts

The energy intensities in the SMC process chain are split between semi-finished parts and final parts manufacturing (Fig. 6). The energy intensities during SMC sheet manufacturing are taken from literature (Table A1). The focus in this case study lies on the modeling of the parts manufacturing stage. In this case study, the compression molding is exemplarily modeled in more detail since it is a relevant process step from an energy point of view due to the process heat requirements. To this end, a hydraulic press is modeled in a physics-based bottom-up machine model. The remaining two process steps (cutting and stacking and finishing) are neglected in the following. Figure 7 shows the machine model of compression molding on a hydraulic press. The processing stage is subdivided into six distinct states that emulate the real process behavior. Two machine components, the hydraulic drive and mold heating, have been identified and modeled. Input parameters are listed as well. They are classified to product, process and machine parameters.

Table 4 summarizes the state-based modeling of power demands during compression molding. The modeled machine is assumed to have a direct pump drive. Opposed to a hydraulic press with a pressure storage reservoir, the direct pump drive only supplies hydraulic pressure, when needed. Therefore, the pump only runs in the machine states closing mold, pressing and opening mold. Mold heating is facilitated with electric heating rods. During ramp-up the mold is heated up from room temperature to the desired processing temperature. Later on, during the process, the heating has to compensate heat losses from conduction, convection and radiation. In addition to heat losses, the mold heats up the SMC sheet to mold temperature during pressing.

The calculation of the energy intensity goes beyond a simple addition of the state-based energy demands. The dynamic modeling of the machine allows for a more accurate prediction of the energy demands. In particular, the energy intensity is calculated in accordance to a more realistic production setting. Waiting times, ramp-ups, shutdowns and their contribution to the part´s energy intensity can be modelled in comparison to a solely static model. Transitions between the machine states occur upon arrival of product entities from the superordinate process chain model. This way, the characteristics of the material flow are directly considered in the simulation.

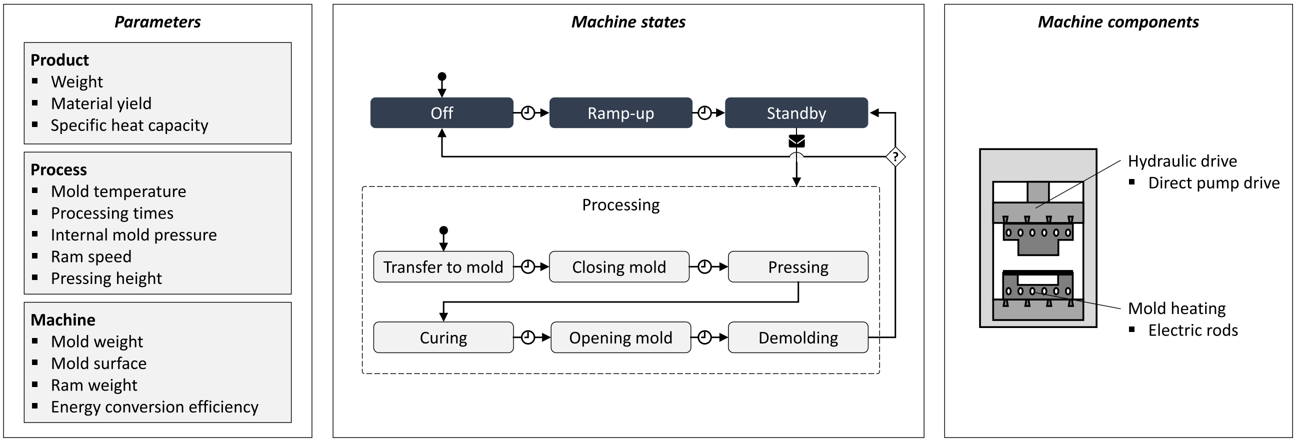


Fig. 7 Machine model of compression molding

Table 4 State-based modeling of power demands during compression molding

Machine state	Power hydraulic drive	Power mold heating
Off	0	0
Ramp-up	0	$\frac{m_{mold} \cdot c_{mold} \cdot (T_{mold} - T_{ambient})}{t_{rampup} \cdot \eta_{moldheating}}$ (5)
Standby	0	$\left(\dot{Q}_{conduction} + \dot{Q}_{convection} + \dot{Q}_{radiation}\right) \cdot \frac{1}{\eta_{moldheating}}$ *with* (6) $\dot{Q}_{conduction} = \frac{k \cdot A_{mold,base} \cdot (T_{mold} - T_{ambient})}{d} \cdot 2$, (7) $\dot{Q}_{convection} = h \cdot \left(A_{mold,base} + A_{mold,lateral}\right) \cdot \left(T_{mold} - T_{ambient}\right) \cdot 2$, (8) $\dot{Q}_{radiation} = \varepsilon \cdot \sigma \cdot \left(A_{mold,base} + A_{mold,lateral}\right) \cdot \left({T_{mold}}^4 - {T_{ambient}}^4\right) \cdot 2$ (9)
Transfer to mold	0	$\left(\dot{Q}_{conduction} + \dot{Q}_{convection} + \dot{Q}_{radiation}\right) \cdot \frac{1}{\eta_{moldheating}}$
Closing mold	$\frac{\left(m_{ram} + \frac{m_{mold}}{2}\right) \cdot g \cdot v_{ram}}{\eta_{hydraulicdrive}}$ (1)	$\left(\dot{Q}_{conduction} + \dot{Q}_{convection} + \dot{Q}_{radiation}\right) \cdot \frac{1}{\eta_{moldheating}}$
Pressing	$\frac{p_{mold} \cdot A_{mold,base} \cdot v_{ram}}{\eta_{hydraulicdrive}}$ (2)	$\frac{\dot{Q}_{conduction} + \dot{Q}_{convection} + \dot{Q}_{radiation}}{\eta_{moldheating}} + \frac{m_{part} \cdot c_{part} \cdot (T_{mold} - T_{ambient})}{t_{rampup} \cdot \eta_{moldheating}}$ (10)
Curing	0 (3)	$\left(\dot{Q}_{conduction} + \dot{Q}_{convection} + \dot{Q}_{radiation}\right) \cdot \frac{1}{\eta_{moldheating}}$
Opening mold	$\frac{\left(m_{ram} + \frac{m_{mold}}{2}\right) \cdot g \cdot v_{ram}}{\eta_{hydraulicdrive}}$ (4)	$\left(\dot{Q}_{conduction} + \dot{Q}_{convection} + \dot{Q}_{radiation}\right) \cdot \frac{1}{\eta_{moldheating}}$
Demolding	0	$\left(\dot{Q}_{conduction} + \dot{Q}_{convection} + \dot{Q}_{radiation}\right) \cdot \frac{1}{\eta_{moldheating}}$

In order to explore the effect of varying input parameters and calculate a realistic range for the energy intensity, a parametric study was conducted. To do so, the complete list of input parameters was scanned for parameters that are likely to increase the energy demand due to longer processing times and/or higher power demands. Since the product concept already defines parameters that are linked with it, e.g. weight, material properties, mold weight and mold surface, these were excluded from the list. The remaining list included three parameters that are displayed in Table 5. These parameters were varied according to a triangular distribution. The table presents the parameters and the corresponding values for the triangular distribution. Altogether, thousand simulation runs were carried out.

3.4 Results for Parts Manufacturing

Table 6 summarizes the results for the production stage. The values presented in the table represent the energy demand on machine level and additionally the energy demands from technical building services. They have been measured and/or calculated based on the explanations in Sects. 3.3.1 for the steel and aluminum concept and Sect. 3.3.2 for the SMC-parts. The ranges displayed in the table represent the results from the parametric study in Sect. 3.3.2. Regarding the SMC parts, the model only calculates the energy intensity on machine level. In order to ensure comparability with the steel reference and the aluminum part, TBS energy demands were additionally considered for the SMC concepts. To this end, an equal energy demand is assumed as in the case of the steel reference. The last column in Table 6 compares the modeled energy intensities with reported data from literature. There is an overlap between literature data and the modeled results. However, with respect to unknown system boundaries and the underlying assumptions form the literature data, a more detailed comparison and interpretation proves to be difficult.

From Table 6 it can be noted that the energy intensity at machine level of the CFRP and GFRP-SMC concepts deviate from each other. This deviation is primarily attributable to the different ranges of input parameters, especially to the internal mold pressure. Figure 8 A shows in this context on

Table 5 Overview of the parameters in the parametric study of compression molding

Parameter	Minimum	Maximum	Mode	Sources
Curing time (s)	60	300	180	[49, 53–55]
Internal mold pressure (MPa)	GFRP: 3 CFRP: 15	GFRP: 10 CFRP: 20	GFRP: 5.5 CFRP: 16.5	[49]
Mold temperature (°C)	130	160	140	[54]

Table 6 Energy intensities during parts manufacturing

Concept	Energy intensity—machine level (kWh/part)	Energy intensity—TBS (kWh/part)	Energy intensity—total (kWh/part)	Energy intensity—total (MJ/part)	Energy intensity—based on literature (MJ/part)
Steel	0.95[1]	0.20[1]	1.15	4.14	–
Aluminum	0.51[1]	0.20[1]	0.71	2.56	–
GFRP-SMC	2.05 – 4.47[2]	0.20[3]	2.25 – 4.67	8.10 – 16.82	12.25 – 63.42[4.)]
CFRP-SMC	5.98 – 7.76[2.)]	0.20[3]	6.18 – 7.96	22.25 – 28.66	7.00 – 36.24[4.)]

[1] Empirically measured data

[2] Simulation result

[3] Assumed based on empirically measured data

[4] Retrieved from literature, see Table A1 for list of references

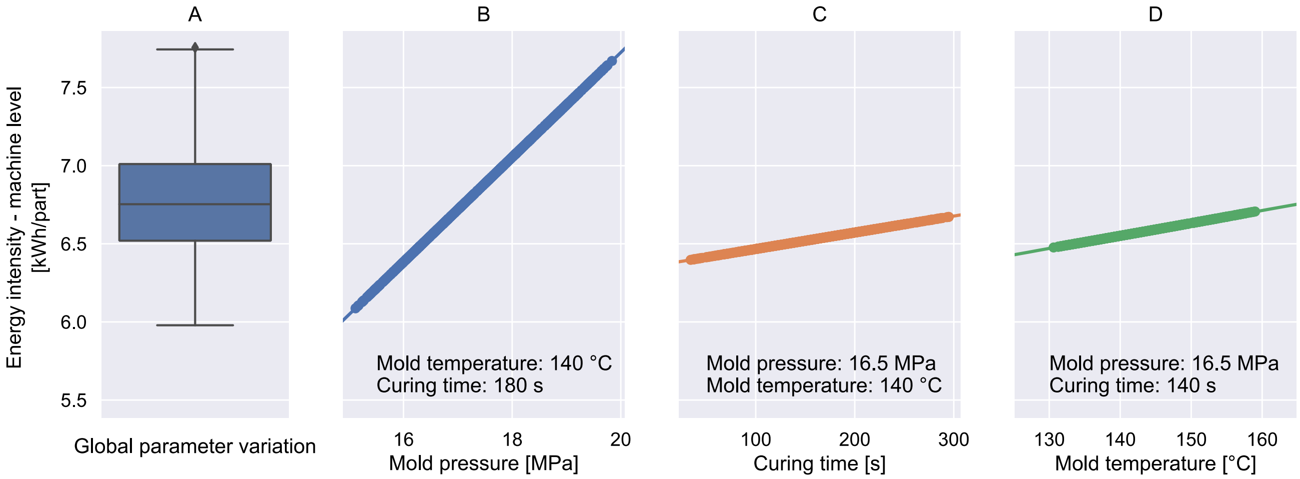


Fig. 8 Results of the parameter variation for CFRP compression molding

the example of carbon fiber SMC the box plot of the energy intensity on machine level when all three parameters had been varied. Next to this, Fig. 8B–D illustrates the model sensitivity on the variation of the three input parameters when varied independently. The upper and lower limits of each input parameter were chosen according to state-of the-art technical boundaries. This ensures that the resulting solution space represents meaningful parameter combinations even if the three input parameters were varied within in a different proportional range. Interdependencies between the input parameters have not been considered in the sensitivity analysis. The internal mold pressure has proved to have the biggest contribution to the energy intensity on machine level. Mold temperature has the second highest impact and curing time the smallest impact. The sensitivity curves have the same qualitative characteristics for glass fiber SMC, as well. This explains the bigger range of the energy intensity of GF-SMC than of CF-SMC (Table 6). In the case of the GF-SMC, the literature values for the internal mold pressure indicated a higher variance than for CF-SMC, which is accordingly represented by the results.

Besides the energy intensities that are in the main focus of the developed approach, also the material intensity of the production processes has been analyzed. The machine models use material yield as a static input factor that is not further detailed. However, it represents an important factor to consider, when it comes to calculating the thermal energy demand for heating processes. When the evaluation perspective is extended to cradle-to-gate, the material intensity becomes even more important due to the high embodied energy of lightweight materials. The material yield for the deep drown body part has been analyzed empirically in the press shop (Table 7). The same material yield of 40% has been assumed for the other design concepts. The material intensity was then calculated based on the material yield and final part weight that is provided by the design engineer. In a successive step (Sect. 3.5), the embodied energy of the parts is calculated based on the material intensity and the energy intensity of material production.

Table 7 Material intensities during parts manufacturing

Concept	Part weight (kg)	Material yield (–)	Scrap material (kg/part)	Material intensity (kg/part)
Steel	6.5[1]	0.4[2]	9.8	16.3
Aluminum	3.2[1]	0.4[2]	4.8	8
GFRP-SMC	3.5[1]	0.4[2]	5.3	8.8
CFRP-SMC	2.0[1]	0.4[2]	3.0	5

[1] Data provided by product designer

[2] Empirically analyzed data

[3] Assumed based on empirically analyzed data

3.5 Modeling Other Life Cycle Stages

The environmental assessment of the alternative concepts is performed in the context of the defined life cycle scenarios and assumptions regarding the production parameters. The environmental assessment methodology is based on the approach presented in an earlier publication [48]. Thereby, the entire component life cycle will be considered. Table 8 summarizes the scope of the applied Life Cycle Inventory model based on [48]. The assessment methodology includes the modeling of a LCI based on material and energy flows within the body part life cycle as well as a Life Cycle Impact Assessment (LCIA) based on that inventory. The LCIA will focus on GHG (greenhouse gas) emissions. The LCI model relies on submodels for different life cycle stages of a body part. The models for the parts manufacturing stage incorporate the results from Sect. 3.4.

3.6 Results of the Assessment from the Perspective of the Whole Life Cycle

In order to explore, where the environmental hotspots are and what factors contribute the most to the savings or additional environmental burdens compared to the reference case, a chart needs to differentiate between each life cycle stage. With this regard, Fig. 9 illustrates the life cycle greenhouse gas emissions of the four parts in the corresponding scenarios. Next to a detailed breakdown on each life cycle stage, the figure illustrates the break-even points (where achieved) in comparison to the steel reference concept. Contributions in the individual life cycle stages can either have a positive amount (materials production and manufacturing stage) and a negative amount (scrap recycling and use stage). The negative amounts in scrap recycling represent environmental credits. Regarding materials production, these are already balanced in Fig. 9. The figure differentiates between the environmental impact of the material used in the final part and the materials that becomes scrap during the production process (due to the material efficiency). During the use stage, the negative amounts describe the weight induced energy savings. The contribution of parts manufacturing of the GFRP and CFRP part is illustrated with an error bar. This represents the variability from the simulation experiment.

Table 8 Scope of the life cycle inventory model, based on [48]

Life cycle stage	System description
Materials production	Provision of raw materials and semi-finished products based on state-of-the art processes, including shares of recycled materials Neglecting market availabilities, efficiency gains and regional influences to materials production (further research required)
Semi-finished parts manufacturing and parts manufacturing	Semi-finished parts manufacturing: Energy demands for different manufacturing routes (steel, aluminum, GFRP, CFRP) based on literature values Parts manufacturing: Process energy and material demands based on empirical values (steel and aluminum) and the introduced simulation approach (GFRP, CFRP, only compression molding, cutting and stacking and finishing were neglected) Parts manufacturing: Energy demands for technical building services for all manufacturing routes based on empirical values Modeling of manufacturing material efficiency yields and reintroduction of production scraps in body part manufacturing and exploited production scraps Influence of renewable electricity supply in manufacturing Consideration of open- and closed loop treatments of manufacturing scrap
Use	Component-based energy demand of electric vehicles Two mobility concepts: ownership vs. MaaS Influence of different electricity mixes for vehicle charging (Germany, China) Neglecting service and repair scenarios (further research required)
End-of-Life	Neglecting in the current study, as location and available treatment processes for end-of-life vehicles is not related to engineering processes in focus of the paper

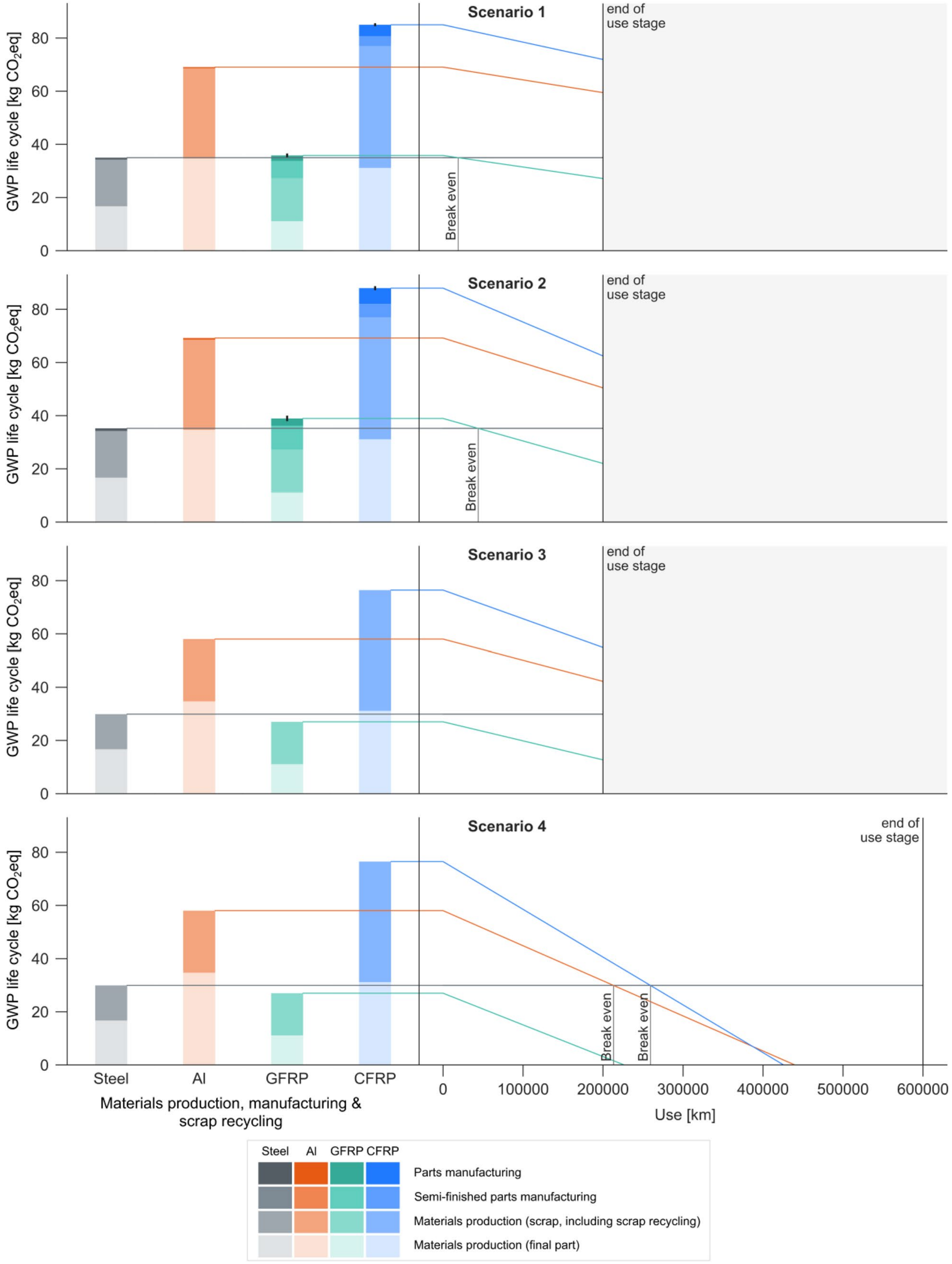


Fig. 9 Life cycle comparison and break-even of the design concepts and scenarios

In scenario 1 and 2 only the glass fiber reinforced SMC can reduce greenhouse gas emissions compared to the steel reference concept. The concepts made of aluminum and carbon fiber-reinforced SMC have no savings potential despite their high lightweight design potential. The reason for this is the energy intensive and thus emission rich material production process together with a low material efficiency in parts manufacturing, which further drives the primary material demand and associated emissions upwards. Although scrap recycling reduces these emissions for the aluminum part, it cannot overcompensate the high embodied material energy of primary aluminum. The fourth scenario (mobility as a service application) brings much higher potentials compared to the other three scenarios (vehicle ownership). This can be explained by a higher mileage and a higher energy reduction value in this this use concept (vehicle usage in an urban environment has a higher energy reduction value). Consequently, the weight savings are more effective and at the same time, they exert their energy saving potential over a much longer period.

Taken together, energy demand during parts manufacturing has a minor share compared to the environmental impact of materials production. Consequently, the renewable electricity supple for parts manufacturing in the future scenarios (scenario 3 and 4) has also only a marginal impact on the total life cycle. Even if the energy intensity of production processes during parts manufacturing has a small contribution on the total life cycle, these charts make the relevance of this life cycle stage apparent. Due to the high embodied material energies of lightweight materials, the amount of production scrap and quality rates of manufacturing processes play a crucial role on the total life cycle.

Figure 10 presents the results from a different perspective than in Fig. 9. The figure tries to direct attention toward the sensitivity of a selected factor (on the y-axis) on the life cycle results. Exemplarily, the relation between a varying material yield and the resulting break-even distance is depicted. The basis for comparison is the steel reference part. The chart only compares the aluminum and the CFRP parts in the respected scenarios. GFRP has been excluded as it represents a predominantly advantageous part from the beginning of the use stage on in comparison to the steel reference. Material yield has been varied between 40% (actual state in the case study) and an idealized 100%. With the help of the diagram, a product or production engineer can explore the effect of increasing the material yield on the total life cycle and the break-even distance. The other way around, they can start with a defined break-even distance and look for a material yield that needs to be achieved in order to reach the defined break-even distance in a given use scenario. To demonstrate it on an example, reaching a break-even in scenario 1 must happen before 200,000 km. This can be achieved by increasing the yield from 40% to about 80%. Obviously, it needs to be clarified whether this can be achieved for the given part and manufacturing process route.

The results indicate that in the current life cycle scenarios (scenario 1 and 2), only the use of glass fiber reinforced SMC is advantageous from an environmental perspective. However, from the perspective of the product designer, it still needs to be carefully examined, whether this material can guarantee the high quality requirements for the surface quality on the vehicle exterior. Instead, the inner parts of the vehicle, which only have to fulfil lower surface quality requirements, seem to be an adequate use case. However, since the greenhouse gas emission savings are relatively low compared to the steel reference, also the economic advantages need to be justified of using glass fiber reinforced SMC´s in body parts. Based on the results, the use of fiber reinforced materials is recommended from an environmental perspective in the future scenarios (scenario 3 and 4). In the case of vehicles in mobility as a service operation, the use of fiber-reinforced plastics for outer parts of the vehicle cannot longer be excluded per se. The reason for that are the expected reduced quality requirements for the surface quality due to decreasing customer relevance in case of a vehicle operation in mobility as a service operation.

4 Summary and Outlook

Assessing the energy and material intensity of the manufacturing of lightweight components and putting them in a life cycle context already in early design phases would

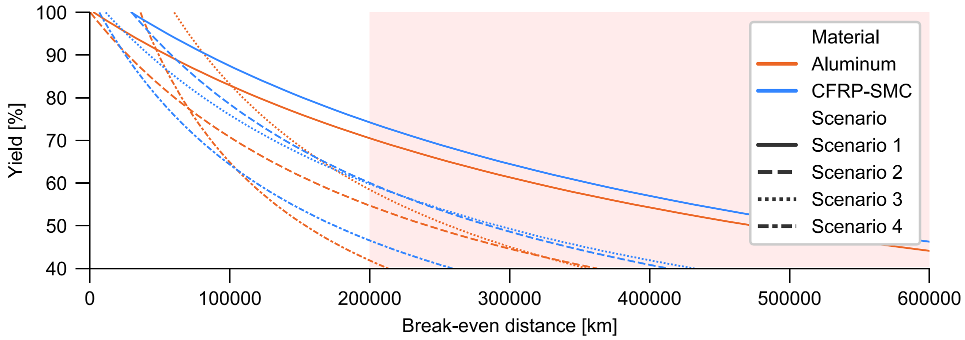


Fig. 10 Sensitivity of the life cycle results exemplarily displayed on the relation between material yield and break-even distance

enhance the possibilities of life cycle engineering. Reviewing existing publications in the context of environmental impact of FRP-based manufacturing processes has underlined the associated challenges for the prospective life cycle evaluation of manufacturing processes of lightweight body parts. Against this background, this paper has proposed a modeling and simulation approach for estimating the energy intensity of manufacturing processes, where life cycle inventory data is not available. The concept was applied on a case study from the automotive industry. Its objective was to analyze the greenhouse gas emissions reduction potential of different door concepts in the life cycle of an electrical vehicle. The results indicate that energy demand in parts manufacturing are off less importance compared to other life cycle stages. However, material yields and quality rates during manufacturing have a considerable impact on the total life cycle.

The proposed concept makes a contribution towards a model-based life cycle engineering of lightweight automotive body parts. The added value of the concept is that the environmental evaluation of design concepts can be made easily accessible for product designers and manufacturing related influencing factors can be made transparent over the whole life cycle. A challenge for the application of the approach is the parametrization of the models. In early design stages, exact product, process and machine parameters are scarce. Therefore, reference values of similar products or estimations have to be used. A possible research direction for future work could be exploring the opportunities of a synergetic combination of various model-based methods in production engineering (e.g. energy-oriented machine simulation combined with numerical process simulation). First approaches in this direction are presented in [47]. Although the methodology was developed serving the case of innovative lightweight body parts in automobile applications, the same principles could be applied to other engineering cases as well.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Availability of data and material The supplementary material includes the complete list of references about energy intensities related with FRP-based manufacturing process routes for automotive structural lightweight body parts from Fig. 2. The supplementary material further includes the parameters and results for the life cycle evaluation of the lightweight body parts of the case study.

Code availability Not applicable.

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