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Integrating environmental impact targets in early phases of production planning for lightweight structures

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Abstract

Increased utilization of multi-material lightweight structures requires the development of new manufacturing processes for large-volume automotive production. Manufacturing processes based on fiber-reinforced plastics tend to be more energy intensive than current steel-based processing technologies, which reduces the environmental advantages of lightweight design. The risk of shifting environmental impacts from the usage to the production stage increases the relevance of life cycle engineering based production planning. This paper presents an approach for integrating environmental impact targets into early phase production planning for manufacturing systems of lightweight structures. In the approach, impact targets are derived from eco-efficiency measures. An exemplary application is presented within the case of FRP patching.

Keywords: Production planning; Life Cycle Engineering; Environmental impact targets

1. Introduction

Legislative measures, an increasing awareness for sustainability and self-imposed efficiency goals drive automotive companies to reduce the environmental impacts of their products and production. Multi-material lightweight structures reduce fuel or energy demands and hence greenhouse gas emissions in the usage stage. However, multi-material lightweight structures and adapted manufacturing processes, tend to pose new challenges from a life cycle engineering (LCE) perspective [1]. Fig. 1 schematically compares a lightweight structure with a reference part over their life cycle on a component scale. Lightweight structures tend to show higher embodied emissions per unit of weight during production of raw materials. This burden could not always be compensated by the reduced amount of material required [2].

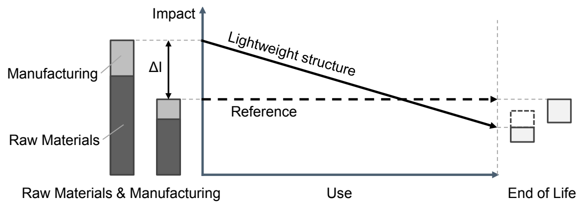

Fig. 1: LCE perspective of lightweight structures [3]

Large-scale production of lightweight structures requires the incorporation of new process technologies and their integration into existing factory environments. Compared to manufacturing conventional steel structures, process chains in the press and body shop for fiber-reinforced plastics (FRP)-based lightweight structures utilize an increased number of thermal process steps as matrix materials need to be heated up to enable the FRP formability. Consequently, the environmental burden of the production stage could increase [4,1].

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In order to justify the application of lightweight structures from an environmental perspective, a break-even between additional efforts from raw materials and production and use stage savings needs to be reached. Additionally, the multi-material design of FRP-based lightweight structures impairs the efficiency of end-of-life treatment processes [1].

Product design changes affecting multiple criteria along the product life cycle, e.g. environmental performance, costs and manufacturability, lead to a multi-criteria decision problem [5]. Shifting impacts from the usage stage to the manufacturing of vehicles increases the relevance of this stage within the product lifecycle. For automotive manufacturers, this additionally leads to a conflict between use stage efficiencies, which depend on product weights, and reducing manufacturing-related impacts. In order to fulfill both goals, it is necessary to combine the product and production perspective within the development of lightweight structures. In this regard, the present paper introduces an approach for integrating environmental impact targets into early phases of production planning for automotive lightweight structures. This intends to enable the evaluation of new manufacturing processes as part of a larger manufacturing system in different production scenarios such as production scales (small, middle or large-scale) and different product characteristics (e.g. expressed as part size or process parameters). The consideration of environmental impact targets in early phases of production planning allows for leveraging improvement potentials, as many aspects of a future manufacturing system are not set in early phases and still have to be decided.

2. Manufacturing of lightweight structures and its challenges from a life cycle perspective

2.1. Manufacturing processes for lightweight structures

Established manufacturing processes for automotive structural components are based on sheet metal processing [6]. FRP-based multi-material structures 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 [7]. Fig. 2 illustrates an overview of an FRP-based process chain. FRP process chains encompass textile processes for semi-finished parts processing and a number of processes depending on part geometry and matrix material for final part production [8]. Hybrid process chains emerge from the combination of intrinsic metal and FRP processing and show promising results towards being a competitive alternative to traditional parts manufacturing. While some manufacturing processes for FRP-based multi-material lightweight structures show high maturity, e.g. measured as manufacturing readiness level (MRL), some other are in lab-scale development [4].

The manufacturing system has to adapt itself to new production processes that differ substantially from the "steel status quo" in terms of manufacturing technology, process times and process chain complexity [9]. In this regard, a major challenge will be to qualify current lab-scale processes with low MRL for high-volume production. Another challenge is to integrate manufacturing processes with high MRL into the established automotive process chain and factory environment, while justifying the advantages from a life cycle perspective [4,1]. Production planning has a significant role in responding to these challenges while operating in an environment of stakeholder´s constraints such as cost, time and quality [10]. Production planning comprises iterative steps of planning and decision-making. The fields of interest vary throughout the planning process depending on the time horizon of planning and production system level. While strategic planning focuses on conceptual issues (e.g. decisions on green-field vs. brown-field, degree of automation or technology selection), the planning tasks become more specific with progressing planning phases with increasing degree of details (e.g. definition of lead time, layout or dimensioning the technical building services). During detail planning, a sequence of process steps and process parameters is defined (e.g. number of machines, tooling concepts, selection of machine types) that transform raw materials and semi-finished products with the help of production factors to final products. [10]

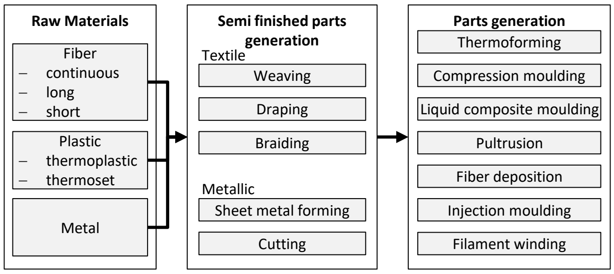

Fig. 2: Process chain for FRP-based multi-material lightweight structures, compiled from [8,4]

2.2. Literature review

Recent research approaches show attempts to support the target-based planning of manufacturing systems in early planning phases. Rödger et al. applied the concept of Sustainability Cone for the planning of a car body production system. The method derives top-down targets from the perspective of absolute sustainability and breaks down environmental and financial targets to each system level [11]. Also, bottom-up approaches have been presented for the life cycle oriented planning of manufacturing systems, e.g. for car body manufacturing [12], for the metal industry [13] and in automotive component manufacturing [14]. These bottom-up approaches support decision making in production planning in the context of energy efficiency improvements and related greenhouse gas emissions of different manufacturing scenarios and process chain alternatives. Guo et al. extend the scope from a gate-to-gate analysis to a life cycle energy analysis of manufacturing alternatives, taking into account the energy footprint of materials production and product manufacturing [15]. The environmental evaluation of new manufacturing processes in early development phases raises questions regarding comparability (e.g. functional equivalence), scale (e.g. lab-scale vs. large-scale), data availability (e.g. missing primary data) and uncertainty (e.g. unknown future industrial scales) [16,17]. The scale-up of lab-scale data to obtain the life cycle inventory (LCI) on industrial scales remains in light of uncertainties challenging [18]. However, the application of simulation methods can contribute to tackle this challenge [16].

Schönemann et al. introduce in this context a multi-level modeling and simulation approach for manufacturing systems for lightweight structures. They combine multiple models on different scales to simulate the accurate energy demand of manufactured products [19].

In order to avoid burden shifting by the introduction of lightweight structures, there is a need for methods and tools that support target-based planning of manufacturing systems in early development phases. Data availability is in early phases a key issue, which is to be addressed by target-based methods for new manufacturing processes.

3. Methodology

The approach intends to integrate environmental impact targets in early phases of production planning for multi-material lightweight structures (Fig. 3). The upper part of Fig. 3 visualizes the decision context, which is the base for planning activities. The approach considers the manufacturing system hierarchy according to [20]. It addresses on a temporal scale phases in production planning; starting form concept over detail planning and procurement to production ramp-up. The bottom part of Fig. 3 integrates a Life Cycle Assessment (LCA)-based procedure of assessing environmental impacts of planning alternatives and translating them to engineering improvement measures for production planners.

At first, the level of manufacturing system hierarchy needs to be chosen. Starting point is a lab-scale manufacturing process that has already proven its technological potential and exceeds a minimum maturity level. Its major environmental impacts are already known in a qualitative manner, e.g. based on process types, e.g. thermal processes, or auxiliary material demands. Relevant environmental impact categories for the LCA need to be identified consistently with the intended manufacturing scenario (e.g. scale of production). Besides known technological issues (e.g. energy intensive process with long cycle time), regional factors (e.g. freshwater scarcity) can be used to derive impact categories. Besides climate change, relevant impact categories for the assessment of manufacturing systems are acidification, human toxicity, abiotic resource depletion, photochemical ozone formation and primary energy demand [11]. Self-imposed targets in the automotive industry focus rather on key performance indicators (KPI), such as energy demand, waste production, freshwater use, solvent emissions and CO_2 emissions [21]. The environmental impact target for the manufacturing system is derived from eco-efficiency measures, e.g. staying below the life cycle environmental impact of a reference part. In this way, product-specific targets can be derived that depend on the lightweight degree, substitution ratio, used materials, etc. The targets are defined within a gate-to-gate perspective, i.e. the targets account for potential usage stage fuel savings and additional efforts in raw materials provision and supply chain.

While background system modeling is facilitated with common LCI databases, a lack of own empirical data in early phases and gaps in LCI-databases hamper the inventory analysis of the foreground system of new manufacturing processes. Fig. 4 presents in this context an approach for modeling & simulating the foreground system. The goal is the provision of substitutes for missing energy and media demands and material flows for the environmental assessment. The approach starts with the identification of critical issues with the objective of building up an understanding of the manufacturing process, its technological potential, use cases in large-scale manufacturing and potential machine components. This serves for clarifying, which process steps need to be performed on the product and which machines and further production equipment are required. The bottom-up approach integrates the results into the modeling of machines and their relevant components on process level according to Fig. 3. Similar to the approach of [19], the machine components provide process conditions that are related to physical quantities. The component-based energy demand is calculated then by employing underlying physical interrelationships. For example, a tempering unit supplies the heat demand of a forming die via a heat transfer medium. The energy demand of the tempering unit consists consequently of the heat demand of the die and losses.

On process chain level, the static energy value stream approach is used to quantify production machines, energy demands and material flows for scaled up production scenarios. Integrating a dynamic view on interrelationships between process steps and technical building services would enhance information quality [22]. To this end, generic process chain models could be applied that allow for a flexible configuration

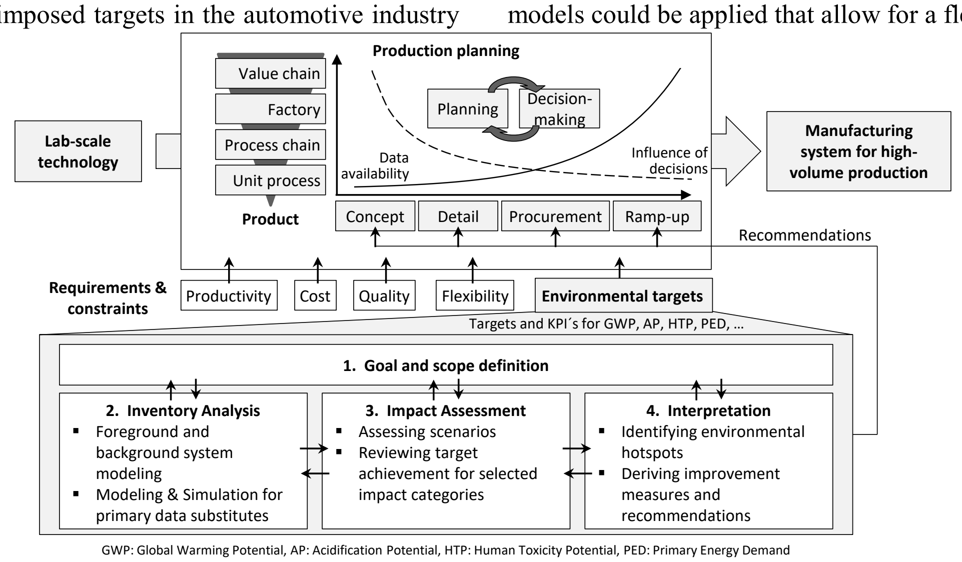

Fig. 3: Integrating environmental impact targets into early phase production planning for lightweight structures

of a process chain and technical building services. Pursuing this goal, detailed machine models from the previous step can be integrated into the process chain simulation model.

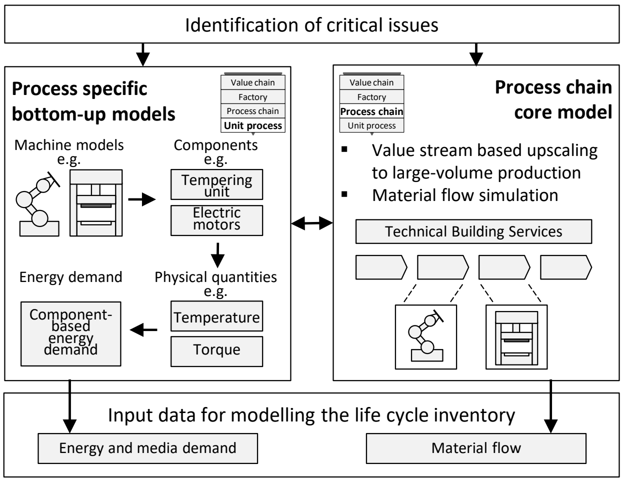

Fig. 4: Approach for modeling the foreground system

The environmental impact assessment translates the life cycle inventory into environmental impact scores. Given that environmental impact targets are named IT_i with $i = 1, \dots, n$ and production process steps $j = 1, \dots, m$, the impact scores IS_i are expressed according to the following equation and then reviewed with respect to each impact target:

$$IT_i > IS_i = \sum_{j=1}^{m} IS_{i,j},\ \forall\, i \in \{1, \dots, n\} \quad (1)$$

The final step closes the loop to production planning by providing relevant information and recommendations by translating the results of the life cycle impact assessment into engineering feedback. In order to derive robust recommendations, it is essential to evaluate different scenarios and possible improvement measures. Three possible outcomes are imaginable depending on the results of the impact assessment (Fig. 5). First, the manufacturing system stays below the defined impact target indicating no further necessary activities (Option 1 in Fig. 5). Second, the manufacturing system exceeds the impact target to a certain amount. The improvement demand ID_i represents the amount that needs to be overcome to reach the target. If the improvement potential IP_i is higher than the improvement demand, the excess impact of manufacturing can still be reduced sufficiently by implementing a set of improvement measures (Option 2 in Fig. 5). In this case, the effect of the possible improvement measures on reducing environmental impact of manufacturing needs to be assessed. Improvement measures are case-specific and can range from optimized dimensioning of machine components over increased utilization of energy efficiency technologies to organizational measures [20]. A detailed analysis of the life cycle inventory can help to identify hotspots in the process chain and derive improvement measures. To this end, environmental impact targets are linked to elementary flows that should not be exceeded (e.g. maximum energy demand or maximum freshwater consumption). The elementary flow targets might be further broken down to each process step. Here, it needs to be decided how the contribution to the target should be shared between process steps. Dividing the allowed impacts equally, based on the share of value creation or process time might be options for this. Ultimately, the goal is to keep the environmental impact of manufacturing below a target value, regardless in which process steps the impact arises. To this end, process steps with high improvement potentials and low associated costs are of high relevance. In the third option, the improvement demand ID_i is higher than the improvement potential IP_i. The set of possible improvement measures is not sufficient for decreasing the environmental impacts of the manufacturing system below the target (Option 3 in Fig. 5).

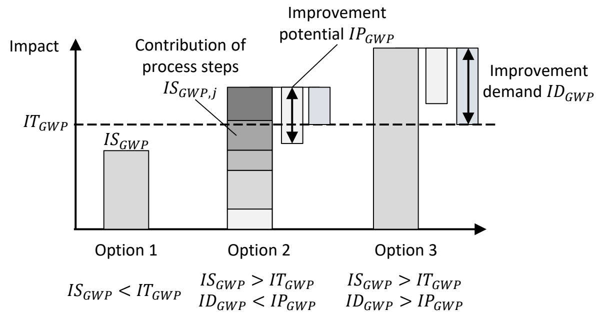

Fig. 5: Interpretation of LCIA-results

4. Application

The presented methodology is exemplarily applied on the case of FRP-patching. The case study includes the stages of raw material extraction, materials production, manufacturing and usage. To illustrate the methodology, only climate change at midpoint measured in kg CO_2-equivalents has been considered. Considering other impact categories would increase efforts on collecting data and require the identification and assessment of the main contributing factors to the specific environmental problem (e.g. use of solvents containing volatile organic compounds or need for freshwater use).

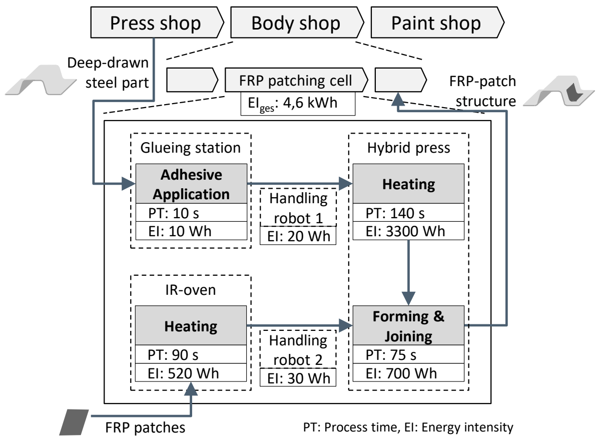

Fig. 6: FRP patching process chain (process times according to [23,24])

4.1. The FRP-patching process

FRP-patched steel structures constitute a compromise between weight reduction and large-scale production costs. Hereby, a steel body-in-white structural component is locally reinforced with patches from glass or carbon fiber reinforced tapes. The patches offer a high range of possible weight savings depending on the geometry and mechanical loads of the structure, fiber and matrix material, fiber volume content as well as number and direction of layers [23]. Fig. 6 illustrates the FRP-patching process chain in the context of series production at an OEM´s value chain. The patching process starts with deep-drawn steel parts from the press shop. Before heating the steel part to the processing temperature, an adhesive is applied to its surface. Parallel, the patches are also heated to the forming temperature. After having reached the processing temperatures, the patches are pressed onto the steel parts and the bonding is formed during cooling down. [23,24]

4.2. Environmental life cycle performance of FRP-patches

In order to derive a gate-to-gate CO_{2eq}-target for the manufacturing of patched structures, usage stage fuel savings, raw materials extraction and material production in the supply chain have been assessed according to following equation:

$$GWP_{Target} = GWP_{Usage} + \Delta GWP_{Materials} + \Delta GWP_{supply\ chain} \quad (2)$$
$$GWP_{Usage} = \Delta m * FRV * GWP_{fuel} * d$$

While fuel savings and avoided steel increase the target, increased utilization of FRP patches decreases it. Lifetime fuel savings are calculated by weight savings Δm, a fuel reduction value FRV of 0.15 l/(100 km * 100 kg) for gasoline vehicles [25] and a total mileage d of 200,000 km. Fig. 7 illustrates the gate-to-gate CO_{2eq}-target for different patched structures from [24]. Different substitution grades and absolute weight savings in these structures (front side member, tunnel, tunnel reinforcement and seat cross member) result in a range of the CO_{2eq}-target. If a total weight reduction of exemplarily 4 kg (1.) is realized by a substitution rate of 25 % (2.), i.e.1 kg steel is replaced by 0.25 kg FRP by same functionality, 1.3 kg FRP replaces 5.3 kg steel. Table 1 summarizes the calculation of the gate-to-gate CO_{2eq} target for manufacturing. The weight reduction of 4 kg vehicle weight leads to usage stage fuel savings of approx. 12 l of gasoline over lifetime, which sums up to 33.96 kg CO_{2eq}. The avoidance of 5.3 kg of processed steel saves additionally 11.11 kg CO_{2eq}. In order to define gate-to-gate targets for the vehicle manufacturer, the production of 1.3 kg FRP patch (PA6/carbon fiber, 60 % fiber volume content) and 0.015 kg epoxy must be accounted for, which were retrieved from the GaBi database, version 8.7, SP 36. This reduces the initial target by 21.7 kg CO_{2eq}, resulting in a CO_{2eq}-target of nearly 23.4 kg (3.). In order to achieve an eco-efficient solution with the exemplary FRP-patched structure, production planning has to assure that this target is not exceeded in high-scale production. As Fig. 7 depicts, the target for the manufacturing is product-specific, it depends on possible weight savings and on the substitution ratio steel/FRP. Lower total weight savings and higher substitution ratios lead due to the higher environmental impact of FRP compared to steel to more ambitious targets for manufacturing.

Table 1: Calculating gate-to-gate targets

Life cycle stages	#	Item	kg CO_{2eq}
Usage stage	1	Fuel (avoided)	+33.96
	2	Steel (avoided)	+11.11
Raw Materials/ Supply chain	3	FRP Carbon fiber PA6	-21.61 18.22 3.39
	4	Epoxy	-0.07
Gate-to-gate target for manufacturing			**23.39**

As energy measurements were not feasible at this phase of process development, the energy demand of the process steps were modeled with static models. To this end, the energy demand on machine level is derived backwards from required process conditions and process times (according to [23,24]), related machine components and its efficiencies. To illustrate this with an example, electrical heating elements provide the heat demand for the forming die to reach forming temperature. Occurring losses during heat transfer need to be compensated by a higher temperature, which leads to an increased power demand of the heating elements, thus energy demand per patched structure. The energy demand of the glueing station and the handling robots is calculated by the assumption of power demand from industrial-scale robots in automotive body shops. The static machine models were aggregated with the energy value stream methodology to calculate the energy intensity of the whole process chain (Fig. 6). The energy demand for manufacturing the exemplary patched structure sums up to 4.6 kWh, which reduces the CO_{2eq}-target by 2.7 kg CO_{2eq} (German electricity mix of 0.594 kg CO_{2eq}/kWh). Combined, the exemplary patched structure is under the target that indicates no need for further improvement measures. However, the energy demand for technical buildings services and a consecutive cutting step were not taken into account.

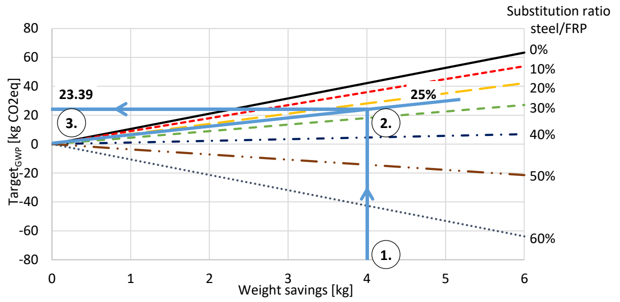

Fig. 7: Gate-to-gate CO_{2eq}-target for the FRP-patch process depending on weight savings and substitution ratio steel/FRP

When the target is exceeded, improvement measures can aim either at increasing the impact target by changes in product design, decreasing the impact in the supply chain or decreasing the gate-to-gate impact of the patching process. Regarding the material, a sourcing of FRP material with a lower environmental impact (carbon fibers based on renewable energy) could be an option. Changes in product design by a different fiber type, matrix material or fiber-volume content could influence weight savings on steel and FRP patches. Furthermore, they could influence processing times and process parameters (e.g. thermoplastics require higher processing temperatures than thermosets) or even the process sequence. These measures might influence the production process and production equipment (e.g. number of handling robots or cell layout), leading to a different energy demand and thus environmental impact. The high flexibility of the patching process regarding the design of patched structures and their use cases within a car body induce a high complexity on the process and supply chain resulting in many different alternative life cycles that can occur. The challenge will be to identify not only the most eco-efficient patch configuration, but also the one that supports the financial targets of the car manufacturer.

5. Summary and Outlook

The current research presents an approach for integrating environmental impact targets into production planning in the context of FRP-based lightweight structures and intends to combine target-based planning with a bottom-up prediction of the environmental impacts of future manufacturing systems. Engaging an LCA-based approach in early phases of production planning offers the possibility of being involved in crucial decision processes that affect the environmental impact of future manufacturing systems. As the access to primary data is limited in early phases, the approach suggests a component based bottom-up modeling for machines and an energy value stream based scale up on process chain level. The environmental targets for high-volume production of FRP-based lightweight structures are derived from eco-efficiency measures in the usage stage. However, in order to achieve a better life cycle performance, the targets need to be more demanding, eventually going beyond eco-efficiency and address the end-of-life stage, as well. As shown in the case study, the applicability of the approach depends on the availability of data. Therefore, further efforts must be invested in developing improved, scalable models that can address product/process characteristics in early development phases.

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