

Design for Agile Manufacturing: Product Design Principles that Enhance Agile Manufacturing of Powertrain Systems

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Abstract—While companies in the entire automotive industry deal with increasing volatility and uncertainty, new trends and innovations pressure especially powertrain margins. The concept of agile manufacturing enables companies to remain competitive in such an environment. As some authors declare that the success of agile manufacturing is largely determined by the design of products, this paper investigates how these two phases in the powertrain lifecycle can be linked. A literature review was conducted to identify DFX guidelines that reflect the agile manufacturing characteristics: flexibility, profitability, speed, proactivity and quality. More than 200 design principles were collected and clustered into seven design objectives according to their main purposes. A first questionnaire was conducted at an engineering company having its main business field in powertrain development in order to define the importance of these principles to enhance agile powertrain manufacturing. The results are presented in a design catalogue. Through an additional literature review the required capabilities of manufacturing systems to fulfill the five agile characteristics were identified. The rating of these capabilities was subject of a second questionnaire at several manufacturing companies in the automotive industry. The employment of a domain mapping matrix supports the selection and application of appropriate product design principles aiming to enhance specific agile manufacturing capabilities. Finally, the developed procedure model was evaluated.

Index Terms—product design principles, agile manufacturing, design for agile manufacturing

I. INTRODUCTION

The modern business environment is characterized through a high degree of volatility and uncertainty. Staying competitive requires companies to continuously adjust their product and service portfolio to the rapidly changing markets and to react to new competitors that are revolutionizing the established industry. As a result, innovation cycles as well as entire product lifecycles are becoming shorter [1]. The high competition has also led to an increasing attention towards customer satisfaction, whereas key concepts are timely and customized products and services. In addition, companies are continuously confronted with unexpected changes caused by global

and diversified markets. The need to cope with such uncertainties and changes has led to the emerge of the agile manufacturing concept [2]. A recent definition of agile manufacturing from Ramsauer et al. (2017) combines the main characteristics mentioned in the literature and describes agile manufacturing as the capability of a company to proactively prepare for uncertainties to enable quick responses to changes across the value chain to exploit business opportunities [1].

Existing literature also deals with the efficient and effective implementation of agile manufacturing, whereas many authors agreed on its close link to product design already some years ago. Besides Kusiak and He (1998) that claim that the success of agile manufacturing is largely determined by the design of products and the system that manufactures them [3], also Lee (1998) perceives the integration of the design of components and their manufacturing systems as the most desirable way to increase system agility [4]. Among other enablers, Gunasekaran and Yusuf (1999) especially emphasize product design as a key for achieving agile manufacturing [5]. Ulrich (1995) even argues that much of a manufacturing system's ability to create variety resides not with the flexibility of the equipment, but with the architecture of the product [6]. The high importance of product design for an effective and efficient enhancement of agile manufacturing but also for the entire product lifecycle is underlined by its strong influence on the committed cost, change cost, and potential cost reduction as illustrated in Fig. 1. Therefore, Ehrlenspiel and Meerkamm (2013) express the significance of a systematic design approach to gain benefits [7].

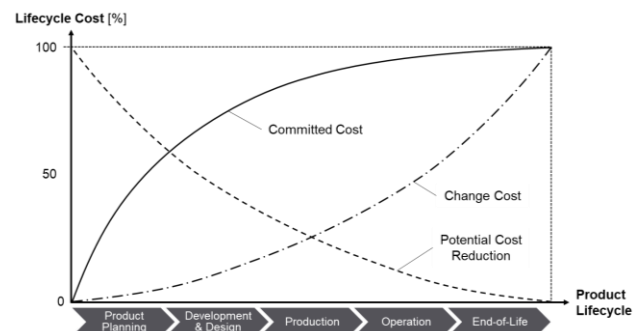


Figure 1. Product lifecycle cost (based on [7] and [8]).

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Especially the automotive industry is nowadays extremely characterized by a high degree of volatility and uncertainty and thus, needs further attention. New mobility business models, autonomous driving, digitalization and electrification have caused an acceleration of disruptions in the industry. Recent studies from Roland Berger and Lazard (2018) have identified a particularly high disruption impact for powertrain systems. Comparing the EBIT margin of the different vehicle domains from 2010 to 2017, the same study also points out that powertrain systems show the biggest decrease, caused by intensified competition, the cost of multiple innovations and the rise of electric vehicles [9]. This results in the need to investigate how powertrain systems can be designed to enhance their agile manufacturing. It can be assumed that a higher capability in coping with uncertainties during the production phase results in an increased competitiveness of manufacturing companies.

II. THEORETICAL BASIS

A. Agile Manufacturing

The literature provides several definitions of agile manufacturing. According to Yusuf (1999) it refers to a company with a manufacturing system that has extraordinary capabilities to meet the rapidly changing market needs. This system can switch quickly between product models and product lines, with a short response time to customer demands [10]. Tsourveloudis and Valavanis (2001) describe agile manufacturing as the ability of an enterprise to operate profitably in a rapidly changing and continuously fragmenting global market environment by producing high-quality, high-performance and customer-configured goods and services [11]. Schurig (2016) investigated 35 definitions of agile manufacturing and identified the following four main characteristics [12]:

- Capacity Flexibility: Range of the economic production capacity.
- Profitability: Improvement of the economic situation (measurable through e.g. EBIT).
- Speed: Quick shifting between product models or lines & Quick adaption of production output to actual demand.
- Proactivity: Preparations to potential changes in the markets upfront.

Based on these characteristics, Ramsauer et al. (2017) define agile manufacturing as the capability of a company to proactively prepare for uncertainties to enable quick responses to changes across the value chain in order to exploit business opportunities [1]. However, as the four main characteristics are rather superficial, additional literature [4], [10]-[14] was investigated to identify the actual capabilities required to fulfill them. This built the basis of a questionnaire aiming to narrow down the capabilities for powertrain systems. The results are presented later on.

Even though agile manufacturing has been discussed in industry and research for almost 30 years, its importance

actually became clear 2007 through the global financial and economic crisis. The following years were characterized by high volatility of sales, unclear geopolitical interrelationships as well as uncertainties regarding economic and technical developments [1]. This underlines the need of manufacturing companies to be capable of coping with volatility and uncertainty by dealing with it proactively. The concept of agile manufacturing can be seen as essential for the success in a such a challenging environment [12].

B. Design Guidelines that Enhance Agile Manufacturing

Product development typically involves high complexity due to a large number of entities and actors cooperating simultaneously with an unpredictable understanding of the customer needs. The desire to meet these challenges in a highly dynamic environment and to ensure that involved designers work towards the same objectives, several researchers have implemented DFX guidelines [15]. DFX can be described as a knowledge-based product design approach with the aim to maximize desirable characteristics such as quality, reliability, serviceability, safety, user friendliness, short time-to-market, etc., while minimizing cost. The X in DFX can have two meanings, namely design for “all desirable characteristics” and design for “excellence” [16]. Research efforts in optimizing product design have led to over 75 different DFX guidelines which have been extended beyond their fundamentals regarding manufacturing (DFM) and assembly (DFA) [17]. In order to link product design with agile manufacturing, design principles of eight DFX guidelines shown in Table I were collected. These guidelines were chosen due to their strong link to the four main characteristics of agile manufacturing mentioned before as well as quality, which can be seen as basic order qualifier. Investigating 13 publications about these design guidelines [15]-[27] has resulted in a collection of more than 200 principles, whereas some were unique, some rather similar and some mentioned repeatedly. Other DFX guidelines with a link to agile manufacturing such as “Design for Switchability”, “Design for Modularity” and “Design for Logistics” were not considered as their main principles were already included in previously investigated guidelines.

TABLE I. DFX GUIDELINES ENHANCING AGILE MANUFACTURING AND THEIR FOCUS (BASED ON [15])

Design for...	Focus of the design guideline
Manufacture	Reducing costly materials and manufacturing process steps.
Assembly	Reducing costly and difficult assembly process steps.
Variety	Reducing the impact of variations on lifecycle costs.
Cost	Reducing lifecycle cost.
Flexibility	Coping with changes in customer needs.
Supply Chain	Enabling logistics and reverse logistics benefits.
Mass Customization	Enabling commonality and reusability of parts and processes.

III. DESIGN CATALOGUE

Summarizing similar design principles and eliminating duplicates has led to a final list of 61 principles. As many of these principles have similar purposes, they were further clustered into seven design objectives shown in Table II. It is important to mention that one design principle can appear in more than one design objective.

TABLE II. DESIGN OBJECTIVES AND THEIR PURPOSES

Design objective	Purpose of design objective
Simplification	Simplifying product and production.
Cooperation/Integration	Enhancing communication between involved entities and actors.
Standardization	Minimizing variants of similar components in different products.
Modularization	Enabling product variants through exchanging independent parts.
Handling	Enhancing quick and save handling of products and components during production.
Processing/Machining	Enhancing the processing and machining of components.
Overdesign	Decreasing the need for product changes in the future.

In order to identify the importance of the remaining design principles to enhance the agile manufacturing of powertrain systems, a questionnaire at an engineering company was conducted. A single case design was chosen due to the uniqueness of the case [28] as well as the opportunity for a greater depth of observation [29]. The investigated company deals with the development, simulation and testing of powertrain systems for different kinds of vehicles and is among the worldwide leaders in this business area. The broad and deep knowledge and experience that has been established within the company further justifies the sufficiency of the single case design. The 14 participants, five manufacturing engineers, four assembly engineers, two supply chain engineers, two project managers for production engineering and quality, and one lead engineer for material technology, rated each design principle from one to five, whereas one stood for low importance and five for high importance. Furthermore, the participants were able to add suitable design principles which they also had to assess. However, as no participants added the same or similar principles, they were excluded from the final result. Calculating the average importance enabled both, the identification of design principles that are currently seen as enhancing agile powertrain manufacturing but also to rank them. This is useful as in many design situations, compromises between different alternatives are necessary. The ranking allows designers to focus on applying the more important principles first before considering others. Table III shows the seven design objectives and their included principles, whereas their importance ranges from 3.00 to 4.92. Furthermore, the average importance of the principles allowed to calculate the importance of the corresponding design objectives. The results show that most of the principles are related to “process and machining”, which

is congruent with the literature as the actual manufacturing process is still the focus of many DFX guidelines. The highest objective importance has “standardization”, followed by “simplification”. This is also understandable as on the one hand, standardization and simplification are strongly linked with each other, and on the other hand, both enable great improvements in several manufacturing related domains such as procurement, processing and machining, handling, etc. Interestingly, “modularization” has a rather low importance, even though the literature regularly mentions this concept as a main enabler for agile manufacturing. A probable reason for that is an underestimation of its benefits for the entire value chain, especially when considering the effects of uncertainties. Finally, the low importance of “overdesign” can be explained as it is often linked with higher cost.

TABLE III. DESIGN OBJECTIVES AND THEIR DESIGN PRINCIPLES (AVERAGE IMPORTANCE IN BRACKETS)

Design objective	Product design principles
Simplification (4)	Design parts that can be assembled easily and only in the correct way (4.92), Simplify and standardize the design and manufacturing processes (4.50), Avoid excessively close tolerances (4.50), Use common materials and components – low cost but high availability (4.25), Reduce number of parts (3.83), Avoid secondary manufacturing operations (3.82), Enable easy tests of major subassemblies and other components (3.75), Provide easy access to surfaces and avoid visual obstructions (3.67), Reduce overall dimensions in order to reduce material (3.67), Use the simplest design addressing the requirements rather than the cheapest or lightest one (3.67), Provide symmetrical parts, or exaggerate asymmetry (3.42)
Cooperation/Integration (3.89)	Use common materials and components – low cost but high availability (4.25), Enable cross functional design activities (4.17), Make quality a primary design goal (3.92), Gather market information for integrating simultaneous engineering (3.83), Formulate a vendor strategy for nonstandard parts and outsourcing early + arrange an early participation of vendors in the design team (3.83), Design a robust product to counter variations in manufacture (3.67), Utilize existing, proven concepts and designs (3.58)
Standardization (4.2)	Use standard/identical materials and components – Create product variants through software; design parts to be multi-usable, etc. (4.50), Use clear, standardized dimensioning of drawings (4.33), Standardize modules and interfaces (4.25), Use standardized design parameters and standards (4.00), Use standardized development and manufacturing processes (3.92)
Modularization (3.74)	Design modules to ensure an easy assembling (4.33), Standardize interfaces between components (4.17), Use independent and interchangeable components (3.92), Changing one product characteristic should not affect more than one module (3.58), Realize delayed differentiation with as many common parts as possible (3.25), Confine functions to single modules (3.17)

Product Handling (3.79)	Ensure simple handling and transportation (4.58), Provide parts that are easy to assemble – lead-in chamfers, automatic alignment, etc. (4.42), Make part differences very obvious to avoid mix-ups (4.00), Ensure rigidity of parts to withstand forces of clamping and machining without distortion (3.83), Provide easy access to surfaces and avoid visual obstructions (3.75), Avoid separate fasteners (3.75), Design parts so that critical dimensions can be controlled by tooling, rather than by the setup of production equipment or by individual workmanship (3.67), Design for easy identification of the state of wear to decide whether a part can be reused (3.58), Optimize dimensions for reducing raw material and weight (3.50), Separating the standard elements/product platform from the variable elements through well-defined interfaces (3.33)
Process/Machining (3.93)	Ensure mistake-proof design with poka-yoke (4.67), Specify optimal tolerances for a robust design (4.33), Use good processable materials in terms of time and cost (4.25), Concurrently engineer parts and processes (4.25), Provide parts that are easy to assemble – lead-in chamfers, automatic alignment, etc. (4.20), Minimize shoulders, undercuts, hard-to-machine materials, specially ground cutters, and part projections that interfere with cutter overruns (4.00), Design machined parts to be made in one setup (4.00), Avoid simultaneous fitting operations (3.82), Avoid machining operations for reducing manufacturing time (3.75), Ensure rigidity of parts to withstand forces of clamping and machining without distortion (3.75), Minimize the number of cutting tools for machined parts (3.58), Use standard machining processes, procedures and sizes (3.50), Design parts so that critical dimensions can be controlled by tooling, rather than by the setup of production equipment or by individual workmanship (3.50), Use general purpose tooling and uniform wall thickness (3.42)
Overdesign (3.59)	Conceive a product with a long-term view of how its components can be effectively and efficiently repaired, refurbished, reused and/or safely disposed in an environmentally friendly manner at the end of the product's life (4.33), Consider product reliability in the design process (4.25), Use a modular design (3.75), Provide symmetrical parts or exaggerate asymmetry (3.67), Use overdesign to avoid product variants (3.50), Select technology which is far from obsolescence (3.50), Increase the number or size of virtual or actual buffer zones (3.17), Preserve space for changes in geometry, orientation, and location of modules (3.00)

IV. AGILE MANUFACTURING CAPABILITIES

Another questionnaire was conducted to narrow down the identified capabilities for the fulfillment of the four main characteristics of agile powertrain manufacturing. Capabilities for “quality” were also added because its importance as order qualifier must not be unconsidered. As there exist several definitions of agile manufacturing and its implementation in the manufacturing industry is rather limited, a multi case design has been chosen to compensate different understandings. The questionnaire included five companies related to the manufacturing of powertrain systems or specific components for the

automotive industry. The ten participants either agreed (1) or disagreed (0) whether the single capabilities are required to fulfill the corresponding characteristics for agile powertrain manufacturing (including quality). Table IV shows these characteristics and the related capabilities with an average agreement of at least 75%. Most of the capabilities are related to actual manufacturing processes. A possible explanation is that a holistic consideration of the entire value chain is still beyond the scope of many manufacturing companies. The results also show that “flexibility”, a concept more commonly known than agile manufacturing, includes most capabilities. “Quality”, actually no main characteristic for agile manufacturing, includes only one capability with an agreement of at least 75%. While this is congruent with the literature, “Customization” is still included in the table as its importance is expected to increase.

TABLE IV. CHARACTERISTICS AND THEIR CAPABILITIES FOR AGILE MANUFACTURING (AVERAGE AGREEMENT IN BRACKETS)

Characteristics	Capabilities for agile powertrain manufacturing
Flexibility	Perform various jobs and reach different goals by using the same set of resources and facilities (100%), Capability to purchase from different sources (100%), Capability of production lines to manufacture different products (100%), Capability of being responsive to diverse demands of customers (100%), Capability of supply chain staff to deal with sudden changes (100%), Broad range of manufacturing capacity (88.9%), Adaptability to changing deadlines (77.8%), Capability to change storage capacity (75%)
Profitability	Cost-effective transforming of manufacturing lines to shift between several products (100%), Cost-effective adjustment of manufacturing capacity (100%), Cost-effective customization (77.8%)
Speed	Short production lead times (100%), Quick transforming of manufacturing lines to shift between several products (100%), Quick product development (88.9%), Quick adjustment of manufacturing capacity (88.9%), Access to information throughout the supply chain (87.5%), Speed of new product introduction (85.7%), Quick access to demand information (75%)
Proactivity	Speed in deployment of new techniques in manufacturing (87.5%), Early identification of possible changes and their time-to-impact (77.8%), Integration of lessons-learned to identify the problems and requirements of the customer (75%)
Quality	Continuous improvement (77.8%), Customization (66.7%)

V. SELECTION OF APPROPRIATE DESIGN PRINCIPLES THAT ENHANCE SPECIFIC AGILE MANUFACTURING CAPABILITIES

Having identified the important product design principles as well as the required capabilities for agile powertrain manufacturing, these two domains are linked through the employment of a domain mapping matrix (DMM) as well as a design structure matrix (DSM) [30]. The procedure model presented in this chapter supports the selection of appropriate product design principles to enhance specific agile manufacturing capabilities. The

first step includes the weighting of the importance of the different agile capabilities which reflect the strategy, capabilities and targets of a particular manufacturing company. Therefore, the following valuation scheme is introduced: must have (9), should have (6), nice to have (3), no need (0) [31]. In the second step, the assessment whether the design objectives positively influence the agile capabilities (1) or not (0) must be performed. Designers and manufacturing engineers working together allows obtaining the most representative results. A generally valid definition of these dependencies is not feasible due to the different characteristics of projects and the varying capabilities of manufacturing companies. The introduction of a corresponding matrix as shown in Table V facilitates these two steps, whereas the DMM used for the following prioritization of the design objectives is also shown.

TABLE V. MATRIX FOR LINKING DESIGN OBJECTIVES WITH AGILE MANUFACTURING CAPABILITIES

Characteristics		Flexi.		Profit.		Speed		Proac.		Qty.	
Capabilities		1	n	1	n	1	n	1	n	1	n
Importance											
Design objectives	Simplify.										
	Coop./Int.										
	Standard.										
	Modular.										
	Handling										
	Processing										
	Overdesign										

In order to support the understanding of the application of this matrix, Table VI presents a sample considering three capabilities within the flexibility characteristic. It is important to mention again, that the numbers in the table are not generally valid and simply serve a presentation purpose. In order to complete the required DMM, the values of the dependencies have to be multiplied by the values of the capability importance (resulting values in brackets).

TABLE VI. SAMPLE APPLICATION OF THE MATRIX

Characteristics		Flexibility		
Capabilities		Purchase from different sources	Different products on one line	Broad range of manuf. capacity
Importance		3	9	6
Design objectives	Simplify.	0 (0)	1 (9)	1 (6)
	Integration	1 (3)	0 (0)	0 (0)
	Standard.	1 (3)	1 (9)	1 (6)
	Modular.	0 (0)	1 (9)	1 (6)
	Handling	0 (0)	1 (9)	0 (0)
	Machining	0 (0)	0 (0)	1 (6)
	Overdesign	0 (0)	1 (9)	1 (6)

Having completed the DMM, the DSM is calculated through the multiplication of the original matrix with its transposed version as seen in (1) from Lindemann et al. (2009) [32].

$$DSM = DMM \times DMM^T \quad (1)$$

The result of the matrix multiplication is illustrated in Table VII, where the prioritization values of the design objectives are shown in the main diagonal (bold values). Dividing these values by the maximum one results in the prioritization percentages displayed on the right side. The maximum prioritization value of a design objective in the DSM depends on the size of the DMM. In this example, the maximum is 243 (if all three sample capabilities in the DMM at Table VI have the highest importance of 9 and the design objective positively influences each of them), which represents 100% as reference. The DSM depicts a project-specific representation [33] of the importance of the design objectives on the enhancement of agile manufacturing capabilities. The percentages indicate the priority of each design objective and thus, build the basis for a focus order recommendation.

TABLE VII. SAMPLE PRIORITIZATION OF DESIGN OBJECTIVES

Simplify.	117									48%
Integration	0	9								4%
Standard.	117	9	126							52%
Modular.	117	0	117	117						48%
Handling	81	0	81	81	81					33%
Machining	36	0	36	36	0	36				15%
Overdesign	117	0	117	117	81	36	117			48%

TABLE VIII. SELECTION OF DESIGN PRINCIPLES DEPENDING ON OBJECTIVE PRIORITIZATION PERCENTAGE

Objective prioritization percentage	Minimum importance of design principles to be applied
1 – 10 %	≥ 4.4
11 – 20 %	≥ 4.2
21 – 30 %	≥ 4.0
31 – 40 %	≥ 3.8
41 – 50 %	≥ 3.6
51 – 60 %	≥ 3.4
61 – 70 %	≥ 3.2
71 – 100 %	≥ 1

Within the single objectives, the prioritization percentage also supports designers to select appropriate design principles. Depending on the resulting percentage value, Table VIII provides the minimum importance value of design principles that should be applied. It is also recommended that the order of applying these principles follows their importance. Assuming that modularity has achieved a prioritization percentage of 48% as in the sample shown in Table VII, design principles with a minimum importance of 3.6 and above should be applied. According to Table III, these are “Design modules to ensure an easy assembling (4.33)”, “Standardize

interfaces between components (4.17)", "Use independent and interchangeable components (3.92)".

VI. EVALUATION

Having developed a design support, two reasons often hinder a full evaluation according to Blessing and Chakrabarti (2009) [34]. First, a lack of the required maturity of the support for its actual application and second, a limiting project duration, which can also be named as obstacle for the presented work. A full evaluation including the application of the developed procedure model on a specific product as well as the investigation of the impact of the resulting product design on agile manufacturing would have significantly exceeded the timeframe. Therefore, the evaluation of the support to select appropriate design principles that enhance specific agile manufacturing capabilities for powertrain systems was performed in two phases. The first phase included semi-structured interviews, performed after completing each questionnaire with the experts at the investigated engineering company. This enabled gathering valuable feedback, whereas its iterative implementation gradually improved the procedure model and enabled a higher orientation to satisfy the actual needs of future potential users. In the second phase, a separate semi-structured interview with an experienced engineer was conducted as final evaluation. The evaluation questions were:

- Is the classification of design principles into design objectives useful for their application and are the objectives suitable?
- Is the importance of the design principles useful for their application?
- Does the procedure model support the selection of design principles that enhance agile powertrain manufacturing and is it applicable for design engineers?

First, the interview partner stated that it is useful to detach the design principles from their original DFX guidelines and classify them into objectives with similar purposes as this increases the understanding for users that are not familiar with the different DFX guidelines. According to the participant, the seven defined objectives cover the most important design areas. Regarding the second question, the interview partner mentioned the usefulness to provide the importance of the single design principles. This supports designers to focus on applying the more relevant principles first when design compromises are necessary. However, the subjectivity of these importance values was a concern. While it is not completely excludable, the authors counteracted this phenomenon by including experts from different departments and hierarchy levels in order to gain objective results. Finally, according to the participant, the developed procedure model supports the selection of design principles that enhance agile powertrain manufacturing. As there are many situations in which design engineers do not exactly know the actual customer

requirements regarding agile manufacturing as well as the best ways to enhance them, this model is seen as potential solution to overcome this challenge.

VII. CONCLUSION

Remaining competitive in the powertrain domain that is characterized through a high degree of volatility and uncertainty requires the application of appropriate design principles as effective and efficient enhancement of agile manufacturing. First, this paper introduces a design catalogue that contains seven design objectives, whereas each objective includes specific design principles. The identification of their importance to enhance agile powertrain manufacturing supports designers to focus on applying the more relevant principles first when design compromises are necessary. Furthermore, capabilities to fulfill the agile manufacturing characteristics for powertrain systems including quality as order qualifier are presented to deepen the understanding in this field. Finally, these two domains are linked through the employment of a DMM. The developed procedure model supports the selection of appropriate product design principles to enhance specific agile manufacturing capabilities. While the iterative evaluation has led to a high orientation to satisfy the actual needs of future potential users, the final evaluation confirms the benefits of the outcomes and the applicability of the procedure model. However, a full evaluation including the actual application of the developed procedure model on a specific product as well as the investigation of the impact of the resulting product design on agile manufacturing is still important to be performed. Only then detailed insights about actual benefits such as time reduction, profit improvement, etc. can be gained. Further research could also focus on coping with uncertainties during the entire product lifecycle through appropriate design objectives and principles instead of only considering the production phase. Therefore, supplementary DFX must be identified, which eventually leads to additional design objectives and principles.

CONFLICT OF INTEREST

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Novelty. The authors state that this work and its results have not been published before and are not submitted to any other journal. The authors declare they have no financial interests regarding this publication.

Ethics approval. All involved parties have approved the publication of this paper and its results.

Consent to participate. All involved parties participated willingly to this work and have approved the publication of this paper and its results.

Consent for publication. All involved parties have approved the publication of this paper and its results.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. While the first author Oliver Moerth-Teo conducted the literature review, Felix Weger developed the design catalogue including its design objectives. Both authors were responsible for the data collection through interviews and questionnaires. All three authors collaborated in the development of the procedure model for the selection of appropriate design principles to enhance specific agile manufacturing capabilities.

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