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Analysis and integration of Design for X approaches in Lean Design as basis for a lifecycle optimized product design

Uwe Dombrowski, Stefan Schmidt*, Kai Schmidtchen

Institute for Advanced Industrial Management, Langer Kamp 19, 38106 Brunswik, Germany

* Corresponding author. Tel.: +49 531 391 2704; fax: +49 531 391 8237. *E-mail address:* stefan.schmidt@tu-bs.de

Abstract

All product lifecycle processes are highly determined by product design. The concept of Lean Design focuses on maximizing customer value and minimizing waste throughout all stages of product lifecycle by an optimized product design. Design for X approaches are essential elements of Lean Design to make the right design decisions by help of concrete qualitative design guidelines. However, Design for X approaches focus on a specific stage of product lifecycle or specific aspect of products or processes, what makes a holistic optimization of product design highly complex. Therefore, the paper analyses the vast range of qualitative design guidelines given in Design for X approaches concerning their effects on product lifecycle and derives recommendations for a lifecycle optimized product design.

Keywords: Lean Design; Design for X; Product Lifecycle; Lean Production Systems

1. Introduction

Manufacturing enterprises have to face increasing customer requirements and a competitive environment. For that reason, manufacturing enterprises have begun to implement Lean Production Systems (LPS). The aim of LPS is to avoid waste in production processes and to align all processes on customer value. Significant improvement potential could be exploited by the implementation of LPS. Therefore, manufacturing enterprises are transferring the basic idea, principles and methods to other enterprise processes, such as product development or after-sales service. [1]

Further improvement potential is expected by this transfer; however, the role of product design on the downstream lifecycle processes is not sufficiently considered. This is due to the fact that the mentioned approaches aim to directly optimize enterprise processes and not the design of the product itself. However, the general conditions for enterprise processes after product development are highly influenced by product design. According to Ehrlenspiel 75% of product lifecycle costs are already fixed by the product design, but only 10% occurring in this stage of product lifecycle. [2]

In order to this fact, the concept of Lean Design has been developed. The aim of Lean Design is to strictly focus on customer value over the entire product lifecycle by help of an adequate product design. Therefore, Lean Design provides concrete qualitative design guidelines for design engineers, however, at a very high level of abstraction. For that reason, these qualitative design guidelines are not a suitable solution for specific design decisions. [3]

In contrast, in traditional product development Design for X (DfX) approaches have been established. These approaches provide qualitative design guidelines for a specific stage in product lifecycle (e.g. Design for Manufacturing), or a specific virtue (e.g. Design for Environment). Compared to Lean Design, these approaches deliver more detailed design guidelines which can be also used in later stages of product development. However, due to their specific focus on a particular stage or virtue, a holistic product design considering all aspects of product lifecycle is highly complex.

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Therefore, Dombrowski et al. suggest a better integration of DfX approaches into Lean Design. For this purpose, a theoretical model for integrating the DfX approaches in Lean Design has been developed already. [3]

Based on this theoretical integration model this paper is going to identify and analyze the vast range of qualitative design guidelines provided in DfX approaches. The analysis aims to identify the influence of qualitative design guidelines on different stages of product lifecycle and other product related targets. Thus, design engineers get a transparent overview of existing qualitative design guidelines and their effects on product lifecycle to make design decisions in a holistic context.

2. Lean Design within an enterprise

2.1. Lean Design objectives

Lean Design has developed from the basic idea of Lean Thinking. This basic idea is to focus on value adding activities from the perspective of the end customer. Consequently, all non-value-adding activities have to be eliminated or at least to be reduced in the lifecycle of a product or service. These activities, which do not contribute to customer value, are referred to as waste. [4] This definition shows that the focus of Lean Thinking is primarily on a direct improvement of processes in which non-value-adding activities occur.

Lean Design aims at the same objective, but follows a different approach. The processes within product lifecycle should not be optimized directly, but the design of the product itself. This approach is based on the fact that 70-80% of customer value and waste that occur in downstream product lifecycle processes depending on design decisions, which are already made in product development. [5] Consequently, Lean Design also strives to increase process efficiency, but by the prospective approach of an improved product design.

Thereby, the product design can be understood as the amount of individual components, their properties and relationships. On the one hand, the customer-relevant properties of a product derive from the defined product design. On the other hand, the necessary processes and activities to generate, maintain and dissolve the product are already implied by the product design. According to Dombrowski et al. three different definitions of a product can be derived depending on the differentiation between product design, value and waste: [3]

- **Design View**: The product is the sum of parts, their properties and their relationships.
- **Value View**: The product is the sum of functions it performs or properties it offers to create customer value.
- **Waste View**: Product is the sum of all lifecycle processes.

In the context of this paper, the consideration focuses on the relationship between the Design View and the Waste View to analyze the effect of product design on lifecycle processes. For that reason, the relation between these two views is discussed in more detail in the following.

2.2. Lean Design focus

According to Ohno, all activities occurring in production processes can be matched to one of the following three groups: [6]

- Value-adding activities
- Non-value-adding but necessary activities
- Waste

Value-adding activities are all activities that directly contribute to customer value. They cover all activities the customer is willing to pay for. [4] In contrast, non-value-adding but necessary activities are all activities that bring no contribution to customer value, however, must be executed under the current working conditions. Therefore, these activities can be reduced but not completely eliminated by help of process optimization. Eventually, waste covers all other non-value-adding activities, which can be completely eliminated under the given working conditions. It can be divided in the 7 types of waste according to Ohno. [6]

The several concept of Lean Thinking basically focus on the elimination of waste and the reduction of non-value-adding but necessary activities. In contrast, Lean Design strives to prevent the occurrence of non-value-adding but necessary activities, because these activities are substantially determined by product design.

This fact should be illustrated by an example from assembly. Two components should be joined with two screws of different size and direction of joining. From the perspective of the end customer, only the coherence of the two components generates customer value. Therefore, the way this coherence is realized is not relevant to the customer. In order to realize this coherence several activities have to be performed. First, the two screws must be grasped and brought to the joining location. Second, they must be screwed for example successively and manually. Furthermore, a tool change can be even necessary due to their different size. However, only the last tightening of the screws generates the traction of the components and so realizes the customer value. All previous activities were necessary to generate customer value, but do not create value for the customer.

According to Lean Thinking, these non-value-adding but necessary activities should be reduced, for example by use of a cordless screwdriver. However, these activities still exist, but they are only executed more efficiently. As a result, Lean Thinking focuses on increasing the efficiency of these activities.

Lean Design aims on designing products in a way to bring the sum of all non-value-adding but necessary activities to a minimum. This is achieved by preventing non-value-adding but necessary activities or converting them to other activities which can be executed more efficiently. Consequently, Lean Design focuses on increasing the effectiveness of these activities.

In this example, the product can be designed in a way, that the two components can be joined by use of only one screw. Thereby, all non-value-adding but necessary activities which are related to the second screw are completely eliminated. The integration of both components in a single component even makes the entire joining process unnecessary. This step eliminates all non-value-adding but necessary activities of the joining process. However, this could result in a more complex manufacturing process. Thus, Lean Design also converts non-value-adding but necessary activities to those, which can be executed more efficiently.

Consequently, all activities can be matched to one of the three groups mentioned. Lean Thinking primarily focuses on the elimination of waste and the reduction of non-value-adding but necessary activities through process optimization. In contrast, Lean Design aims at preventing non-value-adding but necessary activities or at converting them to those, which can be executed more efficiently. This results in a reduction of non-value-adding but necessary activities in total. This fact is illustrated in Figure 1.

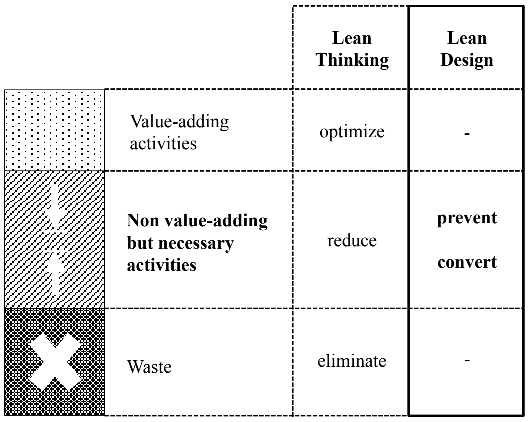

Figure 1: Lean Design Focus

The described classification system can be applied for all stages in product lifecycle. Product lifecycle covers the entire period from idea to disposal of a product. In order to illustrate the effects of product design to the different stages of product lifecycle, an integrated, linear lifecycle model is used [7]. This model emphasizes the stages of product lifecycle after product design. The different stages of product lifecycle are illustrated in Figure 2.

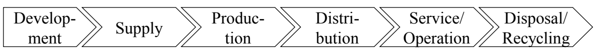

Figure 2: Product lifecycle

The processes within the various stages in product lifecycle impose different requirements for a lean product design. As part of DfX approaches various requirements have already been identified and translated into concrete qualitative design guidelines. Therefore, the DfX approaches are analyzed, classified and integrated in Lean Design in the following.

3. Lean Design and Design for X

3.1. Qualitative Design Guidelines in Lean Design

Lean Design provides a process model and methods, as well as qualitative design guidelines to support design decisions. [5], [8] These qualitative design guidelines are recommendations for design engineers to prevent or convert non-value-adding but necessary activities in the downstream product lifecycle processes. These qualitative design guidelines have a suggestive character. In contrast to prescriptive guidelines, they have to be understood as recommendations rather than strict rules. [9]

The analysis of the provided design guidelines shows that they do not only address the design of a single product, but also address relationships of different products within a product portfolio. This is evident, for example, through the recommendation of using a modular product structure or the use of common parts. [5], [8] However, to transform these qualitative design guidelines into a concrete product design is highly difficult, due to their abstract character. Especially in the later stages of product development more detailed design guidelines are necessary. [10] Furthermore, the influence of individual qualitative design guidelines on the various stages of product lifecycle is not sufficiently specified.

3.2. Integration model for Design for X

For that reason, Dombrowski et al suggest the integration of DfX approaches in the range of methodologies of Lean Design due to the mentioned problems. DfX approaches offer qualitative design guidelines, which are more detailed and related to a specific objective. However, individually they do not aim at a holistic optimization of product design. According to Holt et al. the objectives of different DfX approaches either refer to a stage in product lifecycle or a specific virtue. [11] Table 1 shows a classification of important DfX approaches to the two groups.

Table 1: Classification of DfX approaches [3], [11]:

DfX $_{\text{virtue}}$	**DfX** $_{\text{lifephase}}$
Design for Quality	Design for Assembly
Design for Reliability	Design for Manufacturing
Design for Environment	Design for Service
Design for Logistics	Design for Disassembly
Design for Maintainability	Design for Recycling
Design for Safety	
Design for Remanufacturing	
Design for User-friendliness	

To integrate the different specific DfX approaches in the holistic concept of Lean Design Dombrowski et al provide a theoretical integration model. This model is based on the Characteristics-Properties-Modelling according to Weber [12].

Thereafter, a distinction is made between product characteristics and product properties. Product characteristics are defined and so directly influenced by the design engineer. This includes for example the definition of dimensions, tolerances or the selection of materials. In turn, these product characteristics create product properties that determine the behavior of the product, like reliability, user-friendliness, manufacturability, testability or maintainability. These product properties describe the fulfillment of customer and process requirements. Product properties cannot be set directly by the design engineer, but can be determined by an appropriate set of product characteristics. [12], [13] The relationship between product characteristics and product properties is described by qualitative design guidelines given in the DfX approaches.

For example, design guidelines in Design for Service aim to improve the serviceability (product property) of a product. For this purpose, the design guideline “Avoid sharp edges” provides information which product characteristic (no sharp edges) supports serviceability of the product.

Thus, product properties are addressed by the various DfX approaches and product characteristics are described by the qualitative design guidelines provided. The integration model of Dombrowski at al. is based on this fact and shown in Figure 3:

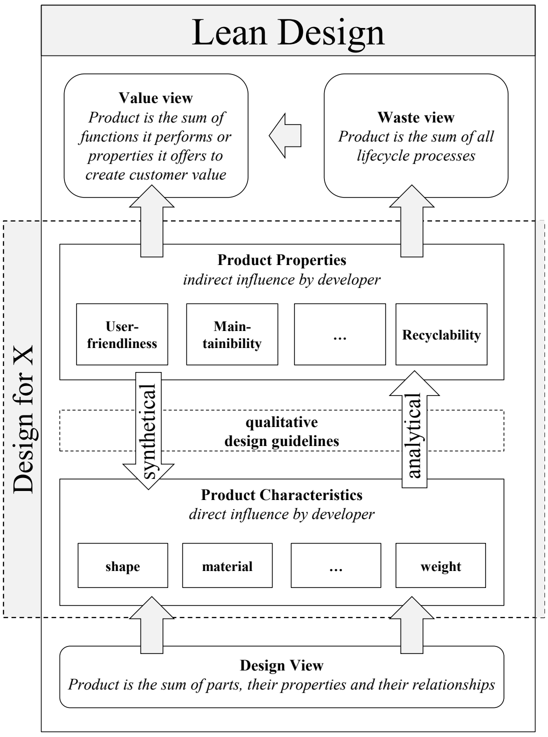

Figure 3: Integration Model for Design for X into Lean Design [3]

As the integration model shows, the connection between the three different views of Lean Design can be established by the differentiation between product characteristics and product properties. Product characteristics are equivalent to the Design View according to Lean Design, while product properties describe the contribution of the product design to customer value (Value View) and the effect on lifecycle processes (Waste View).

By help of the qualitative design guidelines provided in the DfX approaches expected product properties (Value and Waste View) can be derived from given product characteristics (Design View). This analytical approach can be used to evaluate a given design. In contrast, qualitative design guidelines also allow translating required product properties into concrete product characteristics. This synthetic approach can be used to design new products. [12]

4. Analysis of DfX Guidelines

However, this integration model is only a theoretical framework for linking DfX and Lean Design. It does not provide any concrete information which qualitative design guidelines can be used to achieve a holistic product design. In particular, the specific orientation of the DfX approaches and the various competing qualitative design guidelines make a holistic optimization difficult. Therefore, the qualitative design guidelines of different DfX approaches are analyzed in terms of their effects on the various stages of product lifecycle and other product related targets in the following.

For this purpose, 12 DfX approaches were analyzed from 16 sources. Thereby 96 different qualitative design guidelines were identified. According to Bauer more than 300 different qualitative design guidelines can be found in literature [14]. Table 2 gives an overview of the considered DfX approaches, their sources and the number of identified qualitative design guidelines.

Table 2: Overview Literature Analysis

Approach	Source	Number
Design for Assembly	[15], [16], [11], [17], [18], [19]	35
Design for Manufacturing	[15], [18], [20]	13
Design for Service	[19], [21]	11
Design for Recycling	[15], [22], [23]	13
Design for Remanufacturing	[22], [24]	6
Design for Quality	[15], [19], [21], [25]	15
Design for Reliability	[15], [16], [19], [21]	19
Design for Environment	[15], [16], [19], [21]	14
Design for Logistics	[20], [26], [27]	22
Design for Maintainability	[15], [16]	16
Design for Safety	[21]	8
Design for User-Friendliness	[21]	9

In order to optimize product design holistically, it is necessary to determine the effect of different qualitative design guidelines on the various stages of product lifecycle and on other virtues. For this purpose, the 12 DfX approaches were examined concerning identical recommended qualitative design guidelines. An extract of the results of this literature analysis is presented in Table 3.

The qualitative design guidelines are sorted concerning their number of mentions in different DfX approaches. Furthermore, the analysis shows the number of mentions in DfX $_{lifephase}$ or DfX $_{virtue}$ approaches. On the one hand, 40% of the identified qualitative design guidelines are mentioned in more than one DfX approach and thereby affects several product properties. On the other hand, 60% of the qualitative design guidelines are only mentioned in one DfX approach. Therefore, they have a very specific character.

The analysis provides two support functions for design engineers to establish a holistic view of product design. First, a wide range of qualitative design guidelines are gathered from different sources and provided in a compact overview. Second, the analysis points out the qualitative effects of each qualitative design guidelines on several product properties.

Table 3: Analysis of Qualitative Design Guidelines

	Product Characteristic	Product Property														
		DfX lifephase				DfX virtue								Number of mentions		
	Qualitative Design Guideline	Manufacturing	Assembly	Service	Recycling	Remanufacturing	Logistics	Environment	Quality	Maintainability	Reliability	Safety	User-friendliness	**Total**	**Lifephase**	**Virtue**
1.	Minimize the number of parts	x	x	x	x		x	x	x	x	x			**9**	**4**	**5**
2.	Develop a modular design	x	x	x		x	x	x	x	x				**8**	**3**	**5**
3.	Avoid separate fasteners	x	x	x	x	x		x		x	x			**8**	**4**	**4**
4.	Use standard components	x	x	x			x	x			x			**6**	**3**	**3**
5.	Sharp edges, corners, or protrusions that could cause injury shall be avoided			x	x		x			x		x	x	**6**	**2**	**4**
6.	Provide easy access for locating surfaces, symmetrical parts or exaggerate asymmetry		x	x	x					x		x		**5**	**3**	**2**
7.	Design parts to be multi-useable	x			x	x	x				x			**5**	**2**	**3**
8.	Minimize the needs for special tools	x	x	x	x					x				**5**	**4**	**1**
9.	Use of proven components		x						x		x		x	**4**	**1**	**3**
10.	Making the design insensitive to all uncontrollable source of variation								x	x	x	x		**4**	**0**	**4**
11.	Minimize the number of design variants	x	x				x							**3**	**2**	**1**
12.	Provide simple handling and transportation	x	x							x				**3**	**2**	**1**
13.	Design parts that cannot be installed incorrectly (Poka Yoke)	x	x						x					**3**	**2**	**1**
14.	Avoid hazardous and otherwise environmentally harmful materials				x			x				x		**3**	**1**	**2**
…	….													**…**	**…**	**…**
96.	Make the controls and their functions obvious, provide direct feedback from the product												x	**1**	**0**	**1**
	Number of qualitative design guidelines provided	**13**	**35**	**11**	**13**	**6**	**22**	**14**	**15**	**16**	**19**	**8**	**9**			

Thus, design engineers can choose those guidelines, which have a wide effect on product lifecycle or they can select a qualitative design guideline for a specific stage or virtue.

Moreover, the limitations of this analysis should be discussed. First, this analysis only allows a qualitative statement about the effect of specific product characteristics on product properties. Therefore, it gives no information about the strength of the effect. Second, only positive effects on the listed product properties could be identified by literature analysis. That implies that it does not offer any information about possible trade-offs to other product properties. Third, enterprise-specific conditions and preferences are not considered by this analysis.

Consequently, the presented analysis forms a basis for providing an adequate tool for design engineers to make design decisions in holistic context. The mentioned limitations have to be revoked by further research. In fact, the listed qualitative design guidelines have to be analyzed concerning competing product characteristics to identify negative effects on the product properties. Therefore, the qualitative guidelines have to be analyzed by a cross impact matrix and categorized into active, reactive, critical and passive design guidelines. Especially these product properties which are addressed by active, reactive or critical design guidelines must be analyzed concerning possible trade-offs. In contrast, product properties which are mainly addressed by passive design guidelines can be realized with low effects on other product properties. Furthermore, the effects of specific design guidelines have to be quantified that the advantages and disadvantages of design decisions can be weighted. However, the quantification highly depends on product and process specific circumstances within the enterprise, what makes a general quantification unrewarding. Therefore, different quantification scenarios for various product and process circumstances are more expedient. For example, a specific quantification scenario could deliver the quantification for a complex product, which is produced in low volume by low automation. In contrast, a scenario for a simple product with high volume and automation delivers different data for quantification. These quantification scenarios are the basis for fine tuning by design engineers to the individual enterprise specific circumstances. Thereby, a quantitative evaluation of the qualitative design guidelines can be realized. On the one hand, this allows an objective selection of qualitative design guidelines in a holistic context for designing new products. On the other hand, existing design solutions can be evaluated and further improvement potential can be derived.

5. Conclusion

Manufacturing enterprises have implemented Lean Production Systems to meet increasing customer requirements. Furthermore, they have already started to transfer the basic idea of value orientation and waste reduction to other stages of product lifecycle. These attempts only aim on optimizing processes in product lifecycle; however, the essential conditions for these processes are already determined by the product design

Lean Design considers the effects of product design to customer value and on the downstream lifecycle processes. In contrast to Lean Thinking Lean Design does not focus on reducing waste but rather on preventing non-value-adding but necessary activities as well as on converting them in a way they can be executed more efficiently. However, Lean Design does not provide concrete recommendations to support design engineers to make design decisions for this purpose on an adequate level of detail.

For that reason, the paper argued for a closer integration of DfX approaches into Lean Design. DfX approaches provide qualitative design guidelines to improve product design for a specific stage in product lifecycle or virtue. However, the specific orientation of each DfX approach does not support design engineers to make design decisions in a holistic context as it is required in Lean Design.

Therefore, based on the integration model according to Dombrowski et al different Design for X approaches were analyzed concerning their qualitative design guidelines provided. In this case, identical qualitative design guidelines of the various DfX approaches were identified and the effects of different product properties clearly presented.

The analysis can be used as a basis for the evaluation of existing design solutions as well as for the design of new products. However, to provide a powerful tool for design engineers further research has to be carried out. First, the investigation of existing DfX approaches concerning design guidelines provided has to be completed. Second, trade-offs and synergies between different design guidelines have to be identified. Third, the influence of design guidelines on different stages and virtues has to be quantified. Fourth, enterprise specific conditions have to be considered.

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