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The way from Lean Product Development (LPD) to Smart Product Development (SPD)

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Abstract

Lean Product Development (LPD) is the application of lean principles to product development, aiming to develop new or improved products that are successful in the market. LPD deals with the complete process from gathering and generating ideas, through assessing potential success, to developing concepts, evaluating them to create a best concept, detailing the product, testing/developing it and handing over to manufacture. With the beginning of the fourth Industrial Revolution (Industrial 4.0) and the rising efforts to realize a smart factory environment, also product development has to perform a substantial transformation. This paper firstly describes the concept of Lean Product Development as well as new requirements for an intelligent and Smart Product Development (SPD) through the introduction of modern Industry 4.0 related technologies. Based on Axiomatic Design methodology, a set of guidelines for the design of Lean Product Development Processes is presented. These guidelines are linked with concepts from Industry 4.0 in Engineering, showing how a lean and smart product development process can be achieved by the use of advanced and modern technologies and instruments.

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1. Introduction

Product development is already subject to a great change. Products are becoming increasingly complex, global competition and price pressure increases and customer requirements become increasingly individual and difficult to fulfill. This complexity often leads to an increase of effort and lead-time in product development. In recent decades, the introduction of principles and methods of lean management tried to counteract to these conflicts using instruments for efficiency improvement. After the revolution of Lean concepts and principles in the entire field of production science, Lean methods were used successfully in various fields. So e.g. in the field of healthcare (Lean Healthcare), construction (Lean Construction) or in administration (Lean Administration) [1-5]. Also in the area of Engineering, promising methods used in production were applied in Product Development (PD) followed by the creation of new and specific methods for this application [6-7]. The product development area is rich in opportunities for improvement: the length of time to develop a new product, the satisfaction of customer requirements and the way how new products can be produced. This are all areas in which most companies can make dramatic improvements when compared to the most successful companies [6]. Lean Product Development (LPD) can be defined as the application of lean principles to product development, aiming to develop new or improved products that are successful in the market [7].

After this Lean trend, completely new opportunities are arising from new and modern technologies today. The term "Industry 4.0" was created about five years ago and describes the potential based on the introduction of web technologies, an increased digitalization and the networking of virtual and physical value chains. Aim of Industry 4.0 is to realize not only smart, intelligent and cognitive manufacturing systems or factories but also to generate smart products and services. Therefore, also product development has to leave traditional ways coming closer to the development of Industry 4.0.

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This paper gives first an overview of the development and the actual state of the art in LPD. Additionally it describes the new wave of "Industry 4.0" and its expected impact on product development. Following, the way from LPD towards SPD is explained. The authors show the results of an Axiomatic Design based approach to derive guidelines for the design of a Lean Product Development Process. AD is used in this paper to derive design solutions for a Lean Product Development process. Based on this catalogue of design guidelines, the authors describe afterwards how Industry 4.0 concepts can support and encourage the product development process becoming not only lean, but also smart and intelligent.

2. Literature review and theoretical Background

The following part describes the theoretical background regarding Lean Product Development as well as regarding the fourth industrial revolution and its impact on PD.

2.1. Lean Product Development (LPD)

Lean principles have their origin in the Toyota Production System (TPS), which is often used as a synonym for lean production [8]. Later Lean principles were extended also to other branches as Administration, Healthcare, Construction and to Product Development [1-4]. LPD was formally nominated for the first time in the chapter "Technique for Lean Design" in the book "The Machine that Changed the World" [9]. Two kinds of definitions for LPD can be found in literature: an outcome oriented and a process-oriented definition. The outcome-oriented definition describes how LPD can support R&D to improve the quality and functionality of products and thus contribute to the success on the market [7]. The process-oriented definition describes the impact of lean principles to reduce waste and to improve value adding in the internal product development process. Liker and Morgan [10] defined lean product development as: "a knowledge work job shop, which a company can continuously improve by using adapted tools used in repetitive manufacturing processes to eliminate waste and synchronize cross-functional activities." LPD is a cross-functional activity that seeks to uncover product knowledge hidden within the end-to-end production flow, typically in the hand-over points between functional units. LPD deals with the complete process from gathering and generating ideas, through assessing potential success, to developing concepts, evaluating them to create a best concept, detailing the product, testing/ developing it and handing over to manufacture [7].

2.2. Principles and methods of Lean Product Development

Lean Product Development follows the same Lean principles as in traditional lean applications [1] with the target to obtain products/services faster and with fewer costs for the customer: 1) Value, 2) Value stream, 3) Flow, 4) Pull and 5) Perfection. Morgan and Liker [10-11] proposed 13 methods of LPD categorized in three groups: process, people, and technology. Hoppman et al. describe a model for Lean Product Development [12] consisting of 11 elements that are linked together. Dombrowski and Schmidtchen [13] show a broad catalogue of lean methods and categorize them in seven principles of LPD (see Fig. 1).

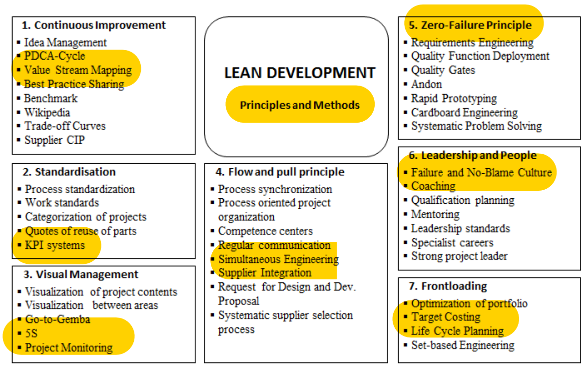

Fig. 1. Principles and methods of Lean Product Development [13]

Industry 4.0 – the fourth industrial revolution

On the basis of an advanced digitalization within factories, the combination of Internet technologies and future-oriented technologies in the field of "smart" objects (machines/products) seems to result in a new paradigm shift in industrial production called also "Industry 4.0" [14]. Traditional products are becoming more and more multidisciplinary, intelligent, networked, agile, and include product-related services. However, not only consumer goods (i.e. smartphones) but also industrial goods are becoming 'smart'. Thus, the engineering of these smart products will be of crucial importance for the competitiveness of industrial companies. There is a need for new Smart Engineering approaches, which also use the latest ICT innovation [15]. Developments in ICT shifted industrial design from the notion of product-as-object to product-as-event [16]. These changes have triggered a variation in professional landscape and new design professions emerged in smart product development activities [17]. Traditionally processes of manufacturing companies can be divided in three pillars [18]:

- Planning, development and validation of the product
- Planning, development and validation of the production system
- Planning, organization of production and order processing.

In a first phase Industry 4.0 has revolutionized particularly the organization in production and the design of production systems. Later than, the concept found its way into product development. The first two pillars can be combined today under the concept of Product Development. Advanced digital tools for PD have been developed in recent years, which can be summarized under the term Product Lifecycle Management (PLM) [18]. Design and drafting methods in all disciplines should be adapted and tested to their suitability for a modern and interdisciplinary design approach. Smart digital tools and solutions are partially available, but need to be further developed and enriched [19].

Current challenges in the field of product development lie in long correction loops when adjustments or improvements are necessary as well as in the validation based on real artifacts. Here Industry 4.0 can support through modern and advanced technologies. Product data should be managed across all processes and throughout the life cycle by ICT. Modern web technologies also enable an entirely new kind of interdisciplinary collaboration across distances [20]. In contrast to product development, Industry 4.0 allows in the production, with its concepts of autonomous self-organization, a shift of the work away from people. In product development, this is just not the case. Industry 4.0 in product development means integration of information and people at many levels and in many different forms. Industry 4.0 opens new ways to customize the product life cycle from scratch [21]. Thus, Industry 4.0 is not replacing lean, but introduces new technological tools, through which the lean principles can be developed properly [22].

3. From Lean Product Development (LPD) to Smart Product Development (SPD)

This section shows an Axiomatic Design based approach to get design guidelines for a lean product development process. Based on these results, industry 4.0 concepts and solutions for a lean and smart product development process are derived.

3.1. Basics on Axiomatic Design Methodology

The Axiomatic Design (AD) methodology was developed by Nam P. Suh in the mid-1970s with the aim to create a scientific, generalized, codified, and systematic procedure for design. Four domains represent the foundation of AD procedure: 1) the Customer Domain, 2) the Functional Domain, 3) the Physical Domain and 4) the Process Domain. The Customer Domain contains the so called customer-benefit attributes (CAs; Customer Attributes), the Function Domain contains the deduced Functional Requirements (FRs), the Design Domain provides Design Parameters (DPs) for the consequent implementation of the FRs, whose transformation into processes shall be regulated by the Process Variables (PVs) in the Process Domain [23]. The AD approach shows an established instrument for the design of complex systems.

The designer is guided by two fundamental axioms moving between the domains. The axioms helps for evaluating and selecting designs in order to produce a robust design [23]:

Axiom 1: The Independence Axiom. The Independence Axiom states that when there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs.

Axiom 2: The Information Axiom. Minimize the information content of the design. It states that the design with the least amount of information is the best to achieve the functional requirements of the design.

The FRs and DPs are described in AD mathematically as a vector. The Design Matrix describes the relationship between FRs and DPs in a mathematical equation [23]:

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{1}$$

An ideal and robust design solution is given by a diagonal and uncoupled Design Matrix (see (1)) when the number of FRs and DPs is equal (Axiom 1) and the information content is zero (Axiom 2) [23]. When the matrix is triangular, the independence of FRs can be achieved only if the DPs are determined by a certain sequence. In this case the Design Matrix is called decoupled ("acceptable design"). Any other form of the design matrix is called a full matrix and results in a coupled or "bad" design [23] and needs revision in design.

3.2. Axiomatic Design based guidelines for the design of a Lean Product Development Process

This section summarizes the AD based derivation of LPD guidelines. AD is used in this procedure to reduce the complexity in a successful application of LPD methods and to derive a set of guidelines how to achieve LPD. Attention has to be paid that the AD methodology itself is not a lean method used to reduce waste in product development. The application of AD starts with the identification of Customer Attributes and their translation in Functional Requirements. Afterwards follows the search for Design Parameter and the decomposition process of FR-DP pairs on different levels. The top-down decomposition goes on since DPs represents solutions that are more concrete. A more detailed explanation of this AD based procedure is described in Rauch et al. [24].

In our case we begin the AD-approach with the identification of customer attributes. The main Customer Attribute for LPD can be described as follows:

CA0 Realization of a product with high quality in a short time for lowest cost gaining the highest value for all stakeholders in the development process.

In a next step this customer need has to be translated into highest level Functional Requirements and Design Parameters for the design of the product development process:

FR0 Improve Customer Value in Product Development
DP0 Lean Product Development Process.

Value can be described as the sum of activities that are focused to be value-adding and therefore to reduce waste in all his different forms and ways. Thus, the FRs are based on the well-known seven types of waste [25]:

FR1 Avoid not target-oriented movement ("movement")
FR2 Avoid non suitable instruments ("processing")
FR3 Avoid unnecessary output ("overproduction")
FR4 Avoid complex Knowledge Mgmt. ("inventory")
FR5 Avoid errors-failures ("failures")
FR6 Avoid inefficient data exchange ("transport")
FR7 Avoid waiting times ("waiting").

Following, the identified FRs need to be translated into practical design solutions or Design Parameters (DP). Based on the above mentioned seven types of waste the FRs on the first decomposition level were defined as follows:

DP1 Collaboration Network Management in PD
DP2 Advanced HW/SW instruments/technologies
DP3 Exact definition of PD output in early phases
DP4 Knowledge Management and storage in PD
DP5 Systematic failure and risk management
DP6 Digitalization of data exchange
DP7 Lead time modelling and acceleration.

The design matrix on the first hierarchical level describes the dependencies of FRs and DPs:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \\ FR6 \\ FR7 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & X & X & X & 0 & 0 & 0 \\ 0 & 0 & 0 & X & X & 0 & 0 \\ 0 & X & 0 & X & 0 & X & 0 \\ 0 & 0 & 0 & X & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ Dp5 \\ DP6 \\ DP7 \end{Bmatrix} \quad (2)$$

The design matrix shows a decoupled design. This means that FRs are not distinguishable in any case from each other. If we have to deal with a decoupled design we have to follow a certain sequence in the implementation of DPs to reduce the system complexity and to prevent loops in the design.

In a next step, the deduced first level DPs have to be decomposed on a second less abstract hierarchical level.

DP1 (Collaboration Network Management in PD) can be further decomposed as follows in table 1:

Table 1. Decomposition DP1 - level 2.

FR_{11}	Avoid information pushed to wrong destination	DP_{11}	Clear addressee and Collaboration Stream Mapping (CSM)
FR_{12}	Avoid not connected users	DP_{12}	Standardized Interfaces and common platform (e.g. Sharepoint)

The design matrix shows again a decoupled matrix because clear addressee (DP11) avoid not connected users (FR12).

$$\begin{Bmatrix} FR11 \\ FR12 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \end{Bmatrix} \quad (3)$$

DP2 (Advanced HW/SW instruments/technologies) can be further decomposed as follows in table 2:

Table 2. Decomposition DP2 - level 2.

FR_{21}	Ensure suitable Mock-up technologies	DP_{21}	Virtual Mock-up software and Rapid Prototyping
FR_{22}	Ensure suitable PD software	DP_{22}	Modern PLM software tools
FR_{23}	Ensure quick and reliable data processing	DP_{23}	Modern Hardware and Internet connection

The design matrix shows a triangular decoupled matrix. Virtual Mock-up software (DP21) requires suitable PD software (FR22) and quick data processing (FR23).

$$\begin{Bmatrix} FR21 \\ FR22 \\ FR23 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP21 \\ DP22 \\ DP23 \end{Bmatrix} \quad (4)$$

DP3 (Exact definition of PD output in early phases) can be further decomposed as follows in table 3. A clear definition of PD output through QFD-technique (DP31) avoids redundancy in the development phase (FR32). Also regular meetings and the division of responsibilities helps to avoid redundant work.

Table 3. Decomposition DP3 - level 2.

FR_{31}	Avoid too much detail and over-engineering	DP_{31}	Definition of PD output (QFD)
FR_{32}	Avoid redundant development	DP_{32}	Regular project meetings and division of responsibilities

The design matrix shows a decoupled matrix.

$$\begin{Bmatrix} FR31 \\ FR32 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP31 \\ DP32 \end{Bmatrix} \quad (5)$$

DP4 (Knowledge Management and storage in PD) can be further decomposed as follows in table 4:

Table 4. Decomposition DP4 - level 2.

FR_{41}	Avoid incomplete information	DP_{41}	Project Manager and Status Review
FR_{42}	Avoid obsolete information	DP_{42}	5S and archiving tools
FR_{43}	Avoid too much information	DP_{43}	Standardization and rules

The design matrix shows again a decoupled matrix. Regular status reviews through the project manager (DP41) help to avoid inefficiency in information management. 5S reduces high buffer stocks of information (FR43).

$$\begin{Bmatrix} FR41 \\ FR42 \\ FR43 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP41 \\ DP42 \\ DP43 \end{Bmatrix} \quad (6)$$

DP5 (Systematic failure and risk management) can be further decomposed:

Table 5. Decomposition DP5 - level 2.

FR_{51}	Avoid failures just from the beginning	DP_{51}	Design and Process FMEA
FR_{52}	Identify and fix failures before they reach the customer	DP_{52}	Regular Design Reviews
FR_{53}	Avoid that failures happen again	DP_{53}	Continuous Improvement and Standardization

The design matrix shows a decoupled matrix.

$$\begin{Bmatrix} FR51 \\ FR52 \\ FR53 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP51 \\ DP52 \\ DP53 \end{Bmatrix} \quad (7)$$

DP6 (Digitalization of data exchange) can be further decomposed as follows in table 6:

Table 6. Decomposition DP6 - level 2.

FR_{61}	Avoid manual data exchange	DP_{61}	Compatible software and database
FR_{62}	Avoid physical transport of data	DP_{62}	Digitalization of PD processes

The design matrix shows an uncoupled matrix.

$$\begin{Bmatrix} FR61 \\ FR62 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP61 \\ DP62 \end{Bmatrix} \quad (8)$$

DP7 (Lead time modelling and acceleration) can be further decomposed as follows in table 7:

Table 7. Decomposition DP7 - level 2.

FR_{71}	Ensure availability of information	DP_{71}	Data and Document Management Systems
FR_{72}	Analyze Lead Time and process flow	DP_{72}	Value Stream Analysis
FR_{73}	Ensure transfer of information	DP_{73}	Automatic workflows in PD
FR_{74}	Avoid to create information too early	DP_{74}	Milestones and Time Planning

The design matrix shows a decoupled matrix. Document Management Systems (DP71) ensure the transfer of information (FR73) and Values Stream Analysis (DP72) as well as automatic workflows (DP73) avoid to create information too early than needed (FR73).

$$\begin{Bmatrix} FR71 \\ FR72 \\ FR73 \\ FR74 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & X & X & X \end{bmatrix} \begin{Bmatrix} DP71 \\ DP72 \\ DP73 \\ DP74 \end{Bmatrix} \quad (9)$$

Using Axiomatic Design, the seven types of waste were analyzed for product development. Through the top-down decomposition approach could be derived basic design guidelines to achieve a Lean Product Development Process.

3.3. Derivation of Industry 4.0 concepts for a Lean and Smart Product Development Process

Fig. 2 shows a graphical overview and structure of the before identified guidelines. In addition are named possible Industry 4.0 technologies, concepts and solutions, which enable and encourage a smarter product development process.

DP1 deals with wastes through wrong sent information or not connected users. Inefficiencies can be reduced by the implementation of ERP-workflows, standardized data formats (e.g. OPC-UA for M2M interaction) and PLM-software. DP2 treats the use of advanced technologies to improve data processing in Product Development.

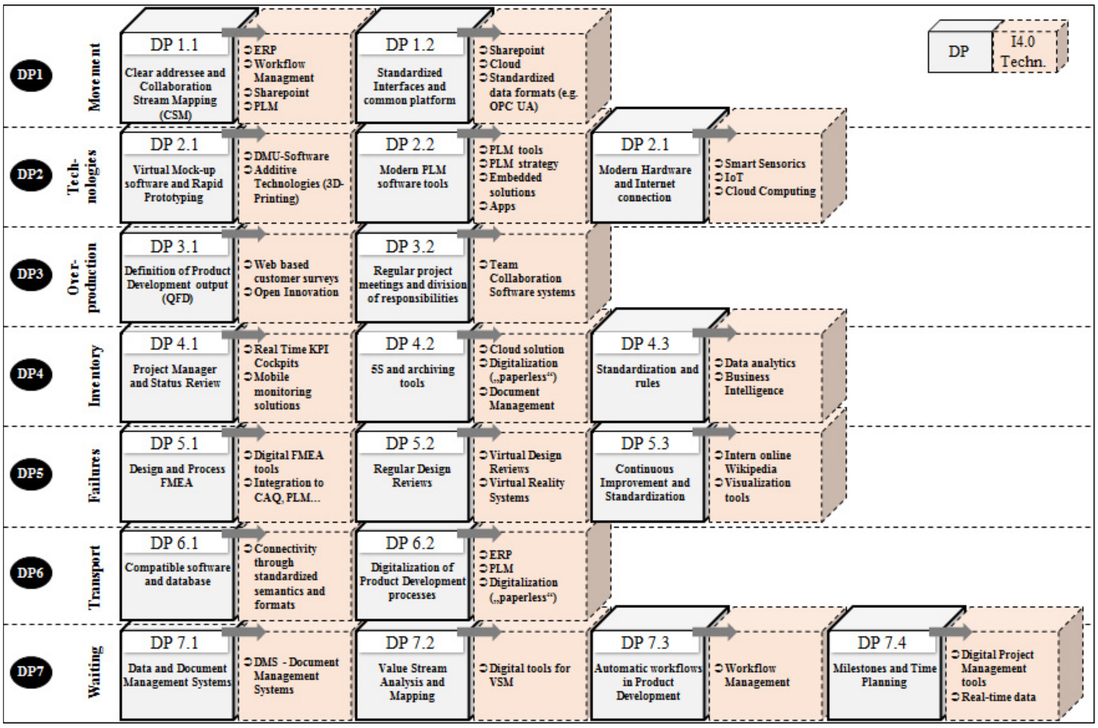

Fig. 2. Industry 4.0 concepts for a Lean and Smart Product Development Process

The use of additive manufacturing technologies (3D-printing) or Digital-Mock-Up (DMU) techniques, smart sensorics, embedded systems and PLM software are important suggestions to increase efficiency in the product development process. DP3 works on the reduction of over-engineering and redundant activities in Engineering. Open Innovation platforms as well as web-based survey techniques offer the possibility to integrate the customer in the product development process and therefore obtain better and more reliable customer requirements. Digitally supported team collaboration systems (e.g. Microsoft Sharepoint) help the product developer and its team to avoid inefficiencies in collaboration. DP4 reduces inefficiencies due to incomplete, obsolete or too much information. Real-time monitoring and data management systems help to provide always complete and “fresh” information to the whole team involved in product development. DP5 tries to reduce failures and to minimize their negative impact through digital FMEA tools or Virtual Design Reviews supporting VR-techniques. DP6 reduces physical transport of data through digitalization of documents and compatible software standards and formats. DP7 reduces waiting times and therefore improves time-to-market. The introduction of Data Management Systems (DMS), workflow management and real-time data exchange enforce time reduction in the product development process.

4. Summary and outlook

The shown Axiomatic Design based approach enables the determination of Lean Design Parameters for a LPD process. Based on the identified guidelines a selection of possible Industry 4.0 concepts and technologies was linked to the single design parameters. This paper aims to illustrate, that Lean Product Development and an Industry 4.0 oriented Smart Product Development are not contrarily but go hand in hand. The objective of Lean Product Development is to reduce wastes in the product development process and to concentrate on value adding activities. Through new and advanced technologies and concept summarized under the term “Industry 4.0” this Lean principles can thus be realized much better and consistent.

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