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Axiomatic Design based Guidelines for the Design of a Lean Product Development Process

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Abstract

After the application of Lean Management in production, the Lean philosophy has been successfully implemented in many other areas. Through lean methods, processes in manufacturing were designed free of waste and through Lean Construction on-site installation follows the customer pace. Actually the Lean approach swaps also increasingly on indirect areas such as Engineering and Product Development. A rising cost sensitivity in product development, even shorter product life cycles and partly unsynchronized processes between R&D and manufacturing made Lean Product Development (LPD) interesting. This research shows an Axiomatic Design based approach to deduce a catalogue of design guidelines for the design of Lean Product Development processes. Based on these guidelines, generally applicable process templates for LPD should be elaborated for lean product development processes.

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Keywords: Axiomatic Design; Lean Product Development; Lean Engineering; Lean Manufacturing

1. Introduction

Based on actual trends towards shorter product life cycles we can identify a great need to accelerate the time for product development. At the same time product development is increasingly under pressure to reduce costs on the product and the product development process. It is therefore important to configure and design the product development process as efficient as possible. In the area of production so called Lean principles, or Lean methods, are applied for many years for the design of lean production processes [1]. By using these methods (for example Value Stream Mapping, 5S, Kaizen,...) waste in operative production processes can be detected and reduced or eliminated. In addition, the process quality and customer satisfaction can be improved through the introduction of Lean Management principles. Lean methods are currently used not only in production but for some years also in other areas such as healthcare, construction or in administration [2, 3]. The use of Lean methods in engineering and product development has been treated only marginally in the scientific literature and is currently in its early stages [4]. The product development area is rich in opportunities for improvement: the length of time it takes to develop a new product; the degree to which the product satisfies the requirements of the customer; and the ease with which new products can be produced are all areas in which most companies can make dramatic improvements when compared to the most successful commercial companies [5]. 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. It is a cross-functional activity, which 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. LPD is performed against a background of continuously assessing and reducing risk of market failure [6].

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Today there are known only single methods and instruments usually taken from Lean Manufacturing and adapted at the requirements of Product or Service Development. There are still missing templates or design-guidelines for the design of Lean Product/Service Development processes. This research aims to develop a universally applicable catalogue of design guidelines for LPD-processes using the methodology of Axiomatic Design (AD). AD has been used for many different issues like Product Development, Manufacturing Systems Design and Organizational Design [7, 8, 9]. By using the AD decomposition and mapping process, Functional Requirements (FR) and the related Design Parameters (DP) will be developed for a lean design of Product Development processes. The result is a catalogue of generally applicable design guidelines for Lean Product Development.

2. Theoretical Background

2.1. Lean principles and Lean Production (LP)

Lean Management is the management of the company through the implementation of Lean principles with the target to obtain products/services faster and with fewer costs for the customer. Lean Management defines 5 Lean Principles [1]:

- Value
- Value stream
- Flow
- Pull
- Perfection

The value is determined by the customer and refers to everything he is willing to pay for. The opposite of value is the definition of waste (Japanese "Muda"): waste are all activities and processes that add no value to the customer. We distinguish two main categories of Muda: there are some not value adding activities that are necessary to generate output and there are other activities creating waste that can be eliminated immediately. The Lean philosophy aims to maximize the value and minimize waste [1]. One of the individuals at the forefront of lean, Taiichi Ohno, enumerated seven forms of waste found in physical production [5, 10]: overproduction, waiting, transportation, incorrect processing, excess inventory, unnecessary movement and defects.

The essence of lean is very simple, but from a research and implementation point of view overwhelming. Lean is the search for perfection through the elimination of waste and the insertion of practices that contribute to reduction in cost and schedule while improving performance of products. This concept of lean has wide applicability to a large range of processes, people and organizations, from concept design to the factory floor, from the laborer to the upper management, from the customer to the developer [5]. The principles of lean management have proved successful in many practical examples and in other areas. Primarily, these principles were used in the production (Lean Production - LP). Lean principles were firstly applied in the Toyota Production System (TPS), which is often used as a synonym for lean production [10]. Later Lean principles were extended also to other functions in the company such as Lean Logistics or Lean Administration. Outside the industrial company Lean Management principles were used in Construction and in Healthcare [2, 3, 11, 12].

2.2. Lean Product Development (LPD)

However, the level of implementation and education in other areas, like product development, is very low.

There is currently a lack in research contributions dealing with Lean Product Development. 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. It 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 [9].

LPD was formally nominated for the first time in the chapter “Technique for Lean Design” in the book “The Machine that Changed the World” [13].

Morgan and Liker [13, 14] proposed 13 principles of LPD categorized in three groups: process, people, and technology. “Process”-oriented principles focus on tasks and sequence of tasks needed for product design. “People”-oriented principles are dealing with organizational culture. “Technology”-oriented principles handle tools for product design and methodical tools for LPD. Main purpose of Morgan and Lickers LPD concept is to improve market responsiveness and customer satisfaction while reducing costs and shorten NPD lead-time [15].

Hoppman et al. show a model for Lean Product Development [16] consisting of 11 elements that are linked together:

- Strong Project Manager
- Specialist Career Path
- Workload leveling
- Responsibility-based Planning and Control
- Cross-project Knowledge Transfer
- Simultaneous Engineering
- Supplier Integration
- Product Variety Management
- Rapid Prototyping, Simulation and Testing
- Process Standardization
- Set-based engineering.

Influenced by the seven wastes in LP WZL and Fraunhofer IPT defined six forms of waste in Engineering [17]:

- Lack of customer orientation (over-engineering, complexity not proportional to customer value, unclear objectives, "moving targets", inaccurate information)
- Interrupted value stream (queues on the critical path, changes and iterations, waiting times, “dormant” projects, lack in synchronization of time and capacity)

- Unused resources (lack of employee motivation, unsuitable distribution / use of existing skills, short-sighted concept development, insufficient skills, communication culture)
- Insufficient standards (none or unfavorable goals and rules for common parts, unnecessary or unmatched detailing of procedures, difficult to find information, unsuitable interfaces and media breaks)
- Unused economies of scale (unused options for common parts, product design without thinking at volumes)
- Defects and rework (consequences of inadequate testing, calculations, etc., unreliable products, product recalls).

Robert Slack [18] found the value principle to be pertinent in the product development context and a specific definition of value was developed which facilitates an understanding of customer value in the product development arena, and assists in creating a customer focus in the lean transition process.

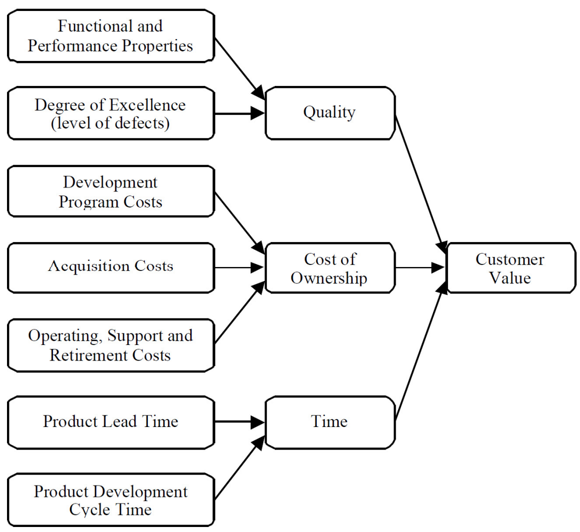

Fig. 1. Decomposition of value in PD [18]

3. Axiomatic Design methodology for the derivation of LPD Process Design guidelines

First, in this section will be given a short introduction in Axiomatic Design (AD). Later will be shown the AD based approach to identify the Functional Requirements and Design Parameters for the design of a LPD process.

3.1. Principles of Axiomatic Design

The Axiomatic Design 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. In order to systematize the thought process and to create demarcation lines between various design activities, four domains represent the foundation of Axiomatic Design procedure: the customer domain, the functional domain, the physical domain and the process domain [19]. 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 [20]. The AD approach was firstly introduced in product development. Later the AD methodology was applied also in other fields and shows today 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 [20, 21]:

Axiom 1: The Independence Axiom. Maintain the independence of Functional Requirements. 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. The Information Axiom is defined in terms of the probability of successfully achieving FRs or DPs. 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 [DM] describes the relationship between FRs and DPs in a mathematical equation [20]:

$$\{FR\} = [DM]\{DP\} \tag{1}$$

An ideal and robust design solution is given by a diagonal and uncoupled Design Matrix (see (2)) when the number of FRs and DPs is equal (Axiom 1) and the information content is zero (Axiom 2) [20].

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{2}$$

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. Any other form of the design matrix is called a full matrix and results in a coupled design [19, 20].

3.2. Identification of Functional Requirements (FR) in the Design of a Lean Product Development Process

As mentioned before AD begins with the identification of customer attributes. In case of the product development process the customer can be interpreted as final user of the product, as well as the producing enterprise. Both stakeholders of the product development process are interested to achieve the highest customer value combined with low costs.

Thus the main Customer attribute can be described as follows:

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

In a next step this customer need has to be translated into Functional Requirements and Design Parameters for the design of the product development process. The related FR and DP, on the highest level, can be described as follows:

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. This statement shows the fundamentals for the definition of FRs on the next AD level in the product development process. If the customer/stakeholder request is to increase value adding activities and to reduce waste in product development processes it is necessary for the AD-approach to know what kind of waste should be treated. Thus, the FRs are based on the well-known seven types of waste [22]:

FR1 Avoid not target-oriented movement
FR2 Avoid non suitable instruments or technologies
FR3 Avoid unnecessary output in PD
FR4 Avoid complex Knowledge Management
FR5 Avoid errors-failures in PD
FR6 Avoid unnecessary transport of goods or information
FR7 Avoid waiting times and therefore long LT.

3.3. Decomposition and mapping process of Functional Requirements (FR) and Design Parameters (DP)

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 Reduction of unnecessary movement in PD
DP2 Improved processing in PD
DP3 Reduction of overproduction in PD
DP4 Reduction of information inventory in PD
DP5 Reduction of failures
DP6 Reduction of transportation in PD
DP7 Reduction of waiting in PD.

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

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \\ FR6 \\ FR7 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & X & X & X & 0 & 0 & 0 \\ 0 & 0 & 0 & X & X & 0 & 0 \\ 0 & X & 0 & X & 0 & X & 0 \\ 0 & 0 & 0 & X & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ Dp5 \\ DP6 \\ DP7 \end{Bmatrix} \quad (3)$$

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 (triangular matrix and path-dependent "good" or useful 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. Improved processing technologies (DP2) have an impact on Knowledge Management (FR4) as well as transport of information (FR6). Reduction of overproduction (DP3) means also a less complex Knowledge Management (FR4). DP4 (reduced information inventory) implies less failure possibility (FR5), less transport of information (FR6) and shorter lead times (FR7). Also DP6 (reduction of transport) leads to shorter lead times. The DPs shown in the design matrix (equation 3) are not concrete enough to define a lean product development process. Thus, in a next step the deduced first level DPs have to be decomposed on a second hierarchical level.

DP1 (Reduction of unnecessary movement 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).

$$\begin{Bmatrix} FR11 \\ FR12 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \end{Bmatrix} \quad (4)$$

DP2 (Improved processing in PD) 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).

$$\begin{Bmatrix} FR21 \\ FR22 \\ FR23 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP21 \\ DP22 \\ DP23 \end{Bmatrix} \quad (5)$$

DP3 (Reduction of overproduction in PD) can be further decomposed as follows in table 3. A clear definition of PD output (DP31) avoids redundancy in the development phase (FR32). Also regular meetings and the division of responsibilities helps to avoid redundant work in the product development.

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.

$$\begin{Bmatrix} FR31 \\ FR32 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP31 \\ DP32 \end{Bmatrix} \quad (6)$$

DP4 (Reduction of information inventory 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).

$$\begin{Bmatrix} FR41 \\ FR42 \\ FR43 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP41 \\ DP42 \\ DP43 \end{Bmatrix} \quad (7)$$

DP5 (Reduction of failures) 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.

$$\begin{Bmatrix} FR51 \\ FR52 \\ FR53 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP51 \\ DP52 \\ DP53 \end{Bmatrix} \quad (8)$$

DP6 (Reduction of transportation in PD) 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.

$$\begin{Bmatrix} FR61 \\ FR62 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP61 \\ DP62 \end{Bmatrix} \quad (9)$$

DP7 (Reduction of waiting in PD) 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).

$$\begin{Bmatrix} FR71 \\ FR72 \\ FR73 \\ FR74 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & X & X & X \end{bmatrix} \begin{Bmatrix} DP71 \\ DP72 \\ DP73 \\ DP74 \end{Bmatrix} \quad (10)$$

Fig 2 illustrates the final design matrix on the second hierarchical level. The axiomatic design matrix has been analyzed using the software Acclaro DFSS. This software supports the system designer to structure the FRs and DPs and allows different visualizations such as design matrix, a FR-DP-tree diagram as well as a flow chart.

As a result of the iterated decomposition process the FR-DP tree (Fig. 3) illustrates the various design levels of the mapping and “Zig-Zagging” process. The entire FR-DP tree in this paper consists of two hierarchy levels. FR-DP pairs marked with blue and the blue lines between DPs and FRs represent a path-dependent decoupled design. If we have to deal with such a decoupled design (triangular matrix and path-dependent “good” or useful design) we have to follow a certain sequence in the DPs. The FR-DP tree has to be read always from left to right. Therefore the AD-based sequence in the FR-DP tree is also a recommendation for the sequencing of design parameters. At decomposition level 1 we can find the seven types of waste in PD. At level 2 the single waste typologies were analyzed in the AD-matrix if they satisfy the first independence axiom. Continuing the decomposition matrix on level 3 and further more and more concrete design parameters can be deduced in a very structured, systematical top-down approach. Through the check of AD-axioms on every design level complexity can be reduced at a minimum.

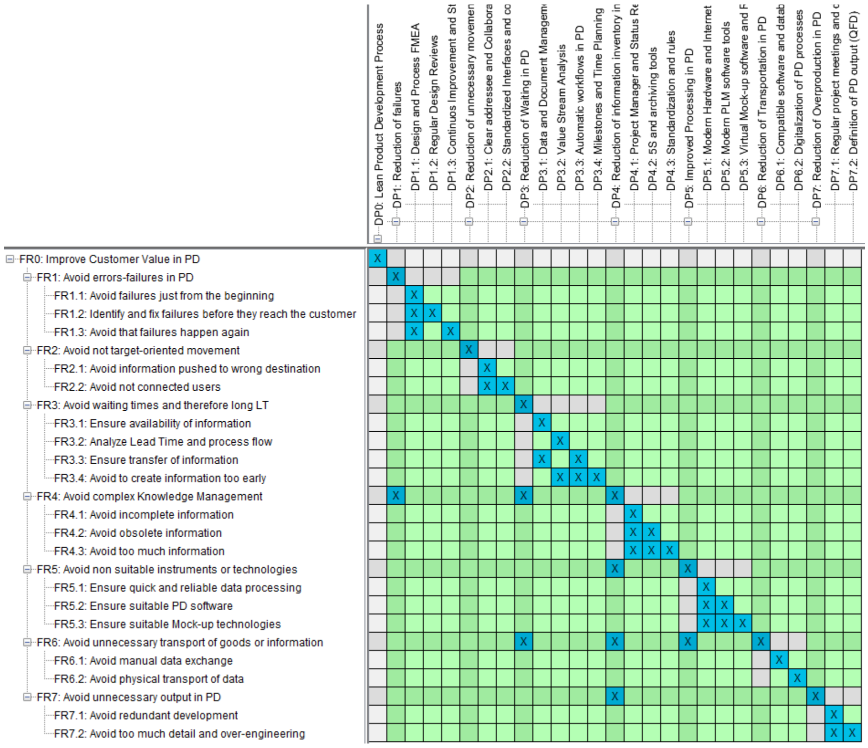

Fig. 2. Axiomatic Design Matrix in Acclaro DFSS

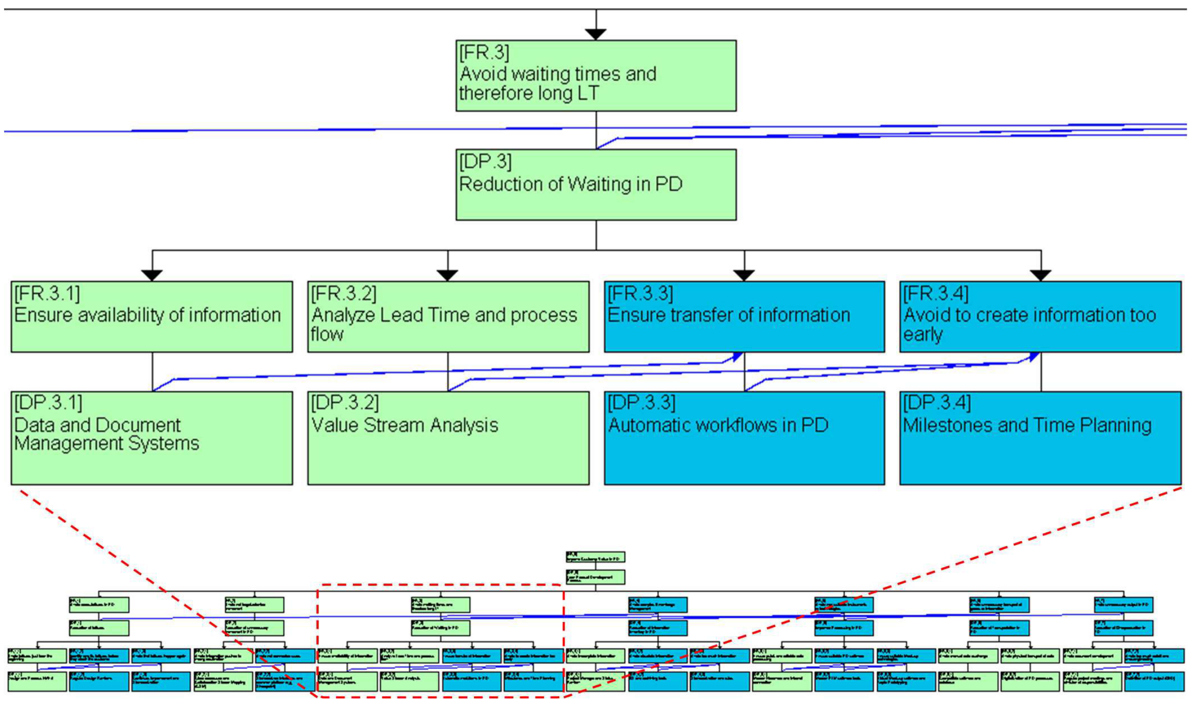

Fig. 3. Visualization of the top-down decomposition in the FR-DP-tree and zoomed screenshot FR3-DP3 (Acclaro DFSS)

4. Conclusion and outlook

The paper started with a brief literature review analyzing the state of the art in Lean Product Development (LPD). There were described different approaches in the design of a more efficient and value-oriented lean product development process.

This research is based on the increase of customer value and thus on the reduction of waste in product development. Using Axiomatic Design as methodology, the seven types of waste were analyzed for product development. Through the top-down Axiomatic Design decomposition approach could be derived first basic design guidelines for a Lean Product Development Process on the second hierarchical level of the FR-DP-tree (see Fig. 3). In part the decomposition revealed concrete methods like FMEA, QFD etc. Other derived DPs are still very abstract and need to be broken down in further hierarchical levels. The axiomatic design matrix showed very often a decoupled design. Therefore a defined sequence should be adapted in the implementation of the identified design guidelines. In addition to the top-down mapping approach AD can be used to determine such an ideal sequence in applying the guidelines to avoid inefficient loops and circular references.

In a next step, the research team will decompose the identified fundamental LPD guidelines into more tangible design solutions and thus break down the FR-DP tree on further hierarchical levels.

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