A Framework for Organizing Lean Product Development

Joern Hoppmann, ETH Zurich
Eric Rebentisch, Massachusetts Institute of Technology
Uwe Dombrowski, Technische Universität Braunschweig
Thimo Zahn, Technische Universität Braunschweig

Abstract: While in the last 20 years a large number of frameworks have been presented in literature, currently there is no consensus on how to define Lean Product Development (PD). We used content analysis to investigate existing approaches and integrated them into a single, coherent framework consisting of 11 Lean PD components. To better understand the nature of the novel definition of Lean PD, we conducted a theoretical investigation of the component interdependencies. We hypothesize that Lean PD needs to be understood as a system of highly interwoven components that only in their concurrency lead to high performance in PD.

Keywords: Lean Product Development, Lean Engineering, Lean Innovation, Product Development System, Lean Thinking, Innovation Management

EMJ Focus Areas: Innovation & New Product Development, Operations Management, Program and Project Management, Systems Engineering

Since the publication of *The Machine that Changed the World* by Womack et al. (1990), the concept of Lean Thinking has attracted increasing attention from practitioners and scholars around the world. Lean Thinking propagates taking a close look at an organization's value streams, eliminating all non-value adding activities, and consistently aligning all required activities to the external and internal customers. The results—and particular characteristics of any Lean system—are short lead-times, reduced requirements for human and financial resources, as well as products that are particularly suited to fulfill customer requirements (Womack and Jones, 1996).

It has long been argued that Lean Thinking has to be applied to the entire value stream rather than to distinct subsystems within a company (Murman et al., 2002; Womack and Jones, 1996). Despite this notion, which is reflected in the ultimate goal of the "Lean Enterprise", up to this point the application of Lean principles has strongly focused on the domain of production. While there is abundant experience with introducing Lean on the manufacturing shop floor, concepts on how to employ Lean in up- or downstream processes and supporting functions remain to be investigated in nearly as much detail.

Arguably, an area with a particularly high potential for realizing the benefits of Lean principles is the field of product development. Product development by definition plays a key part in defining customer value. It determines the physical appearance of the product, defines the materials to be used and, thus, largely constrains the set of production processes that can be employed to manufacture the product. Consequently, the impact on cost, quality, and manufacturing lead-times is usually much bigger in the phase of product development than during production (Kennedy, 2003; Morgan and Liker, 2006).

Current market trends put increasing pressure on companies to optimize their product development processes in three major dimensions: time, cost, and quality. First and foremost, increasing speed of innovation requires companies to drastically reduce their development cycles and minimize time-to-market. "In automotive product development, since the 1980s the average time to develop a car from styling to freeze has decreased by about one-third—to 24 months in 2006" (Morgan and Liker, 2006). In automotive product development, since the 1980s the average time to develop a car from styling to freeze has decreased by about one-third—to 24 months in 2006. Second, lower sales volumes per product with a simultaneous increase in product complexity have resulted in an increased cost pressure. If one seeks to avoid an increase in the development cost per unit produced, total development costs for a product with a smaller sales volume have to be much lower than for a product with a larger sales volume. Third and last, shortening product life-cycles comes with a decreased tolerance for quality issues. High rates of early failures after market introduction, causing lengthy efforts of rework, are even less acceptable for a product with a short life-span than they are for long-lived ones (Morgan and Liker, 2006).

Lean Product Development (PD) as a domain addresses these major challenges. It discusses how the general idea of Lean Thinking can be applied to the field of product development to achieve a value-oriented, resource-efficient, and fast product innovation process. To this end, several authors have studied instances of product development systems, particularly the Toyota Product Development System. During these studies a number of components were identified that are supposed to contribute to the previously mentioned objectives and distinguish a high-performing Lean PD system from traditional PD. Up to this point, however, the exact number and nature of the elements that make up a Lean PD system remain controversial.

With this article we contribute to the theory base of Lean PD in order to enable further productive empirical research in this area. We give an overview of existing frameworks for Lean PD and combine them into a single, clearly structured theory framework. We begin with a review of existing approaches to Lean PD, following with a description of the method we used to derive a novel, coherent definition of a Lean PD system consisting of eleven Lean PD components. We then analyze the interdependencies among the system elements. The components of the framework are described in more detail in the subsequent section. Next we summarize the insights generated through the theoretical analysis of the component relationships. Finally, we conclude by discussing the implications of our research for the theory of Lean PD and point to potential future research.

Refereed research manuscript. Accepted by Special Issue Editor Geert Letens.

A Historical Perspective on Approaches to Lean Product Development

The basis for understanding Lean PD, although not yet termed this way, was laid through a series of detailed studies of product development systems by Clark, Chew, Fujimoto, and Sheriff even before *The Machine that Changed the World* was published. In their study *Product Development in the World Auto Industry* (1987), Clark et al. compared the product development performance of 22 projects of international automotive manufacturers and found that Japanese companies outperformed North American and European competitors, particularly with regard to engineering hours and lead time. European and American development projects required on average about 3.5 million engineering hours and took about 62 months. Projects of Japanese car manufacturers—despite including a higher number of unique parts—were completed on average with 1.155 million engineering hours within 42.6 months (Clark etl al., 1987). Based on a number of statistical tests, Clark et al. attributed this difference in productivity to the strong involvement of suppliers in the design process and the role of a "heavy-weight project manager" with extensive authority who lead the multifunctional teams through the problem-solving cycles. In addition, Clark et al. found that Japanese product development projects made use of overlapping development stages to a larger extent than projects of European or American car manufacturers (Clark etl al., 1987). The hypothesis that this overlap could contribute to the significantly shorter lead times was subsequently confirmed by follow-up analyses conducted by Fujimoto, Clark, and Sheriff (Clark and Fujimoto, 1989; Cusumano and Nobeoka, 1990; Fujimoto, 1989).

In *The Machine that Changed the World*, Womack et al. (1990) took on the detailed findings of Clark, Chew, Fujimoto, and Sheriff and elaborated on the potential explanations for the tremendous difference in product development performance between Japanese and western automobile manufacturers. While the major impact of their book has been in the area of manufacturing, more than 30 pages of *The Machine that Changed the World* were dedicated to the idea of Lean Design and Lean PD. Under the title of "techniques for lean design" Womack et al. identified four major design methods that differentiated a mass from a lean producer: a powerful project leader with a strong authority, teamwork, early and controlled communication, and simultaneous development (Womack et al., 1990).

In the following years, the idea of overlapping phases and simultaneous development was the one that attracted the most interest of researchers and practitioners. In their effort to find methods to shorten lead times, a number of authors studied cross-functional integration, team structures, and communication and coordination techniques (Liker et al., 1996). The new findings resulted in expansions of the four characteristics of Womack. As an example, Karlsson and Ahlstrom (1996), studying the product development system of a manufacturer of mechanical and electrical office equipment, developed their own interpretation of Lean PD. According to their definition, Lean PD is comprised of six techniques: supplier involvement, simultaneous engineering, cross-functional teams, integration of activities, a heavy-weight team structure, and strategic management of projects.

The strong focus on simultaneous development as the reason for the superior performance of Japanese car manufacturers in product development was in part questioned by the findings of Ward et al. (1995) and Liker et al. (1996) who pointed out that the best in class, Toyota, neither collocated its teams nor intensively communicated with its suppliers. Building on experiments with design automation conducted by Ward and Seering (1989a, 1989b) and intensive studies of practices at Toyota, Ward et al. developed what they called set-based concurrent engineering. In essence, they found that paradoxically, in the case of Toyota, delaying decisions and following a large number of alternatives for the same product module contributed to better and faster product development (Liker et al, 1996; Ward et al., 1995).

The theory of set-based concurrent engineering, particularly attractive due to its counter-intuitive nature, was a strong impulse for the revision and expansion of existing Lean PD concepts. In a manuscript from 2001, published posthumously in 2007, Ward describes a Lean PD system consisting of five major principles: "value focus," "entrepreneur system designer, "set-based concurrent engineering," "cadence, flow and pull," and a "team of responsible experts" (Ward et al., 2007). Kennedy, referring to work with Ward during a study at the National Center for Manufacturing Sciences, names set-based concurrent engineering as one of the four critical elements of Lean PD next to "system designer entrepreneurial leadership," "responsibility-based planning and control," and an "expert engineering workforce" (Kennedy, 2003).

To further explore the particularities of Toyota's approach, Morgan conducted a two-and-a-half year, in-depth study of Toyota's product development system. Through more than 1,000 hours of interviews held with Toyota and supplier representatives at different sites in the U.S. and Japan, Morgan tried to answer the fundamental question what underlying characteristics made Toyota's approach to product development so successful. Together with Liker, who had been strongly involved in the investigation of set-based engineering, Morgan published his findings in *The Toyota Product Development System*, in which the authors identify 13 Lean PD principles they group into the three broad categories: process, people, and technology (Morgan and Liker, 2006).

The comprehensive and detailed description of Toyota practices given by Morgan and Liker has induced researchers to test whether or not the principles described as the reasons for Toyota's success could be found to foster better product development performance in other companies as well. To this end, in two independent studies Brown (2007) and Schuh et al. (2007) surveyed 400 and 143 manufacturing firms respectively and linked the use of particular Lean PD practices to performance indicators. Both found that the use of particular practices is correlated with the success of product development projects as measured by the adherence to schedule, product and product development costs, product quality, revenues, and market share. Interestingly, these practices show strong overlap with the principles of Lean PD defined by Morgan and Liker. Schuh et al. (2008), based on their findings, describe 10 key principles: motivation, value system, design sets, product architecture, product line optimization, value stream definition, capacity planning, synchronization, perfection, and derivation. Brown (2007) lists 13 components he identifies to have the largest impact on improving performance: product development using design sets, value stream mapping, standardized work methods, concurrent design, lean change/process improvement enabled at all organizational levels, information flow aligned with process flow, centralized/documented engineering knowledge, advanced search technologies, knowledge based engineering, digital manufacturing, specialty tools for lean, product portfolio management, and product development results measured with timely metrics.

In summary, over the last 20 years a number of publications on Lean PD have emerged; however, our review of literature on

Lean PD revealed two major problems. First, so far, the empirical base for Lean PD remains rather weak. Much of what has been published on Lean PD is based on insights generated through the early studies of Clark et al., theoretical investigations by Ward and Seering, as well as the comprehensive case studies conducted by Morgan, Liker, and Sobek. The latter, however, have strongly focused on practices at Toyota. Up to this point there are few studies that have tried to collect empirical data on Lean PD from sources other than Toyota. Second, there is a clear lack of a consistent theory base for Lean PD. Existing descriptive frameworks for Lean PD, despite showing apparent overlaps, differ considerably regarding the focus and the number of components they comprise. So far, none of the approaches discussed above has found wide-spread acceptance. Hence, to date it remains largely unclear what particular elements make up a Lean PD system.

It seems likely that much of the first problem, the lack of empirical data on Lean PD, is due in part to the second one, i.e. the lack of a consistent guiding theory basis. The current ambiguity in the understanding of Lean PD represents a major obstacle to progress in this nascent area of research. As a basis for future empirical studies on Lean PD, we therefore took a closer look at the existing approaches, examined the overlaps between the different definitions, and integrated them into a single, coherent, and robust framework for Lean PD.

Study Approach

The goal of our research was not to present a review of Lean PD literature in its classical sense. A rigorous review of the literature published in this field using the well-established procedure was conducted by Baines et al. (2006). Our study focused on a different objective—namely to further a common understanding by distilling and integrating the essential elements of existing approaches toward Lean PD. Our analysis does not address the underlying Lean philosophy or logic that prompted the development of these elements, but rather focuses on understanding the artifacts and their role as part of a system. This approach might, therefore, not directly result in the development of a theory of Lean PD systems, but is an essential step in developing a coherent empirical basis for that theory development.

For this study we used content analysis and applied it to a large number of publications in the field. Content analysis, which has its origin in social sciences, provides a systematic way of filtering and clustering data from recorded human information (Holsti, 1969; Neuendorf, 2005). Using coding procedures, texts are scanned for specific patterns that are used to generate condensed insights on the content. In literature, depending on the purpose of the analysis, different procedures for conducting content analysis have been described. Since in our case the analysis aimed to extend the theory base of Lean PD, we borrowed on an approach described in grounded theory (Charmaz, 2006; Glaser and Strauss, 1967; Strauss and Corbin, 1990). Grounded theory suggests deriving research theory in a systematic way by gathering and analyzing large amounts of data up-front. In the course of the data analysis process the collected data is coded, divided into concepts, grouped into categories, and finally translated into a theory that intends to explain the phenomenon (Corbin and Strauss, 1990). Data, in the original definition by Glaser and Strauss, are "all statements about events pertaining to the area under study" that explicitly include writings of other researchers in the field (Glaser and Strauss, 1967).

For our analysis, we used a sample of 27 publications that are listed in Exhibit 1. To identify this sample, we conducted a web search on "Lean Product Development", "Lean Development" and "Lean Innovation" using the search engines Google scholar and Google. Limiting our scope to journal articles, books, and benchmarking reports, this resulted in 21 retrievable publications being identified (similar searches using the Social Sciences Citation Index and ABI/Inform Global yielded fewer but redundant citations). We checked these publications for whether or not they explicitly mentioned any of the three key words and provided a description of at least one component of a Lean PD system. This resulted in 13 publications that met our criteria for the sample (see column "Explicitly mentions Lean PD/Innovation?" in Exhibit 1). In a second step, we scanned the references in these publications for additional original sources that provided empirical evidence or further detail for the components listed in the 13 articles. This procedure, which explicitly included conference proceedings as research outlets, resulted in 14 publications that were added to our sample.

After selecting the 27 sources for our analysis the publications were coded in two major steps. In the first step, we scanned the publications for quotes describing elements of a Lean PD system. A total number of 316 quotes each consisting of one to four sentences were extracted from the publications on Lean PD and documented in a long list. Subsequently, we used a procedure called "open coding" to label the quotes regarding underlying concepts (Strauss and Corbin, 1990). In an iterative process, the resulting concepts were subsequently checked for overarching themes and clustered into 11 categories. When deriving the 11 categories, care was taken that the category names did not represent general principles or goals, such as "value orientation", but rather processes, technology, or functional roles that could be implemented in an organizational setting. Furthermore, a main goal when defining the categories was to avoid redundancy. Hence, the categories—in the following called Lean PD components—were chosen such that they were mutually exclusive and collectively exhaustive.

In the second major step, we used another round of coding to extract interdependencies between the components we had identified in the first step. Literature was scanned for quotes describing positive or negative effects that the Lean PD components have on each other. The relationships between the components were extracted from the quotes and entered into a cause-effect matrix of 121 fields spanned by the eleven components. Since not all pairs of components' cause-effect relationships had been described in literature, we continued our theoretical investigation of Lean PD by phrasing hypothetical interdependencies for those that had not been explicitly discussed. For this purpose, we drew on our comprehensive analysis of the components in the first step of our analysis and formulated potential links to describe how a particular component required the use of another.

Overall, our analysis of the literature on Lean PD revealed that our list of 27 publications could be broadly separated into two general categories. While the majority of publications focus on describing a smaller number of Lean PD elements in greater detail, we identified some that take on a systems perspective and make suggestions on how to integrate the components into an overarching framework. The latter publications, that are somewhat identical to the ones discussed in the previous section, are marked in the right column of Exhibit 1.

The results of our content analysis will be discussed in the following sections. In accordance with the methods we used, we will first describe the eleven Lean PD components we identified to constitute a Lean PD system. Building upon this, the cause-effect matrix we derived in the second part of the analysis is presented.

Exhibit 1. References Used in the Content Analysis

No.	Reference	Sort of Source	Explicitly mentions Lean PD/Innovation?	Primary Framework Source?
1.	Ballée and Ballée, 2005	Journal article	X	
2.	Brown, 2007	Benchmarking report	X	X
3.	Clark et al., 1987	Journal article		X
4.	Clark and Fujimoto,1989	Journal article		
5.	Cusumano and Nobeoka, 1990	Working paper		
6.	Cusumano and Nobeoka, 1998	Book		
7.	Fiore, 2004	Book	X	
8.	Fujimoto, 1989	Thesis		
9.	Fujimoto, 1999	Book		
10.	Haque and James-Moore, 2004	Journal article	X	
11.	Karlsson and Ahlstrom, 1996	Journal article	X	X
12.	Kennedy, 2003	Book	X	X
13.	Liker et al., 1995	Book		
14.	Liker et al., 1996	Journal article		
15.	MacDuffie et al., 1996	Journal article	X	
16.	Mascitelli, 2007	Book	X	X
17.	Morgan and Liker, 2006	Book	X	
18.	Oppenheim, 2004	Journal article	X	
19.	Schuh et al., 2007	Benchmarking report	X	X
20.	Schuh et al., 2008	Conference proceeding		
21.	Sobek et al., 1998	Journal article		
22.	Sobek et al., 1999	Journal article		
23.	Thomke and Fujimoto, 2000	Journal article		
24.	Ward et al., 1995	Journal article		
25.	Ward and Seering, 1989a	Conference proceeding		
26.	Ward et al., 2007	Book	X	X
27.	Womack et al., 1991	Book	X	X

Eleven Components of Lean Product Development

Exhibit 2 summarizes the results of the first step of the content analysis described in the previous section. The left column lists the 11 Lean PD components that were identified as categories for the elements of Lean PD described in the literature. The columns to the right detail to what extent each category is covered by the Lean PD literature identified as primary framework sources. It should be noted that, due to the approach used to derive the categories, the number of components listed for a particular author in Exhibit 2 naturally differs from the one described later in the article. As an example, Karlsson and Ahlstrom (1996) list simultaneous engineering and cross-functional teams as separate parts of a Lean PD system. In the framework derived in this research these two concepts were, since related, subsumed under the common heading of "simultaneous engineering".

As Exhibit 2 shows, most authors, when describing key principles of Lean PD, focus on a rather small number of elements. The only approach that comprises all eleven Lean PD components building the framework of this article is the one by Morgan and Liker (2006). Their framework was found to be very comprehensive; however, the 13 general Lean PD principles Morgan and Liker describe are broad and sometimes not mutually exclusive. To give an example, Morgan and Liker list "Utilize Rigorous Standardization to Reduce Variation, and Create Flexibility and Predictable Outcomes" as one of the principles for their "process" dimension. This principle shows considerable overlap with "Use Powerful Tools for Standardization and Organizational Learning" which is part of the "tools & technology" dimension of their framework.

In what follows, the 11 Lean PD components of the novel framework are described in greater detail. We explain the background of the components listed in Exhibit 2 and point out why their use has been found to contribute to a stream-lined and cost-efficient product development process.

Strong Project Manager

The concept of the Strong Project Manager, also known as the "Heavyweight Project Manager" or the "Chief Engineer", has its origins in the U.S. aerospace industry and was adopted by the Japanese aerospace industry as it began licensing and building U.S. aircraft in the 1950s (Hall and Johnson, 1970). Its basic

Exhibit 2. Coverage of the Eleven Lean PD Components by Selected Authors

Lean PD Component	Clark et al. 1987	Womack et al. 1991	Karlsson and Ahlstrom 1996	Ward et al. 2007	Kennedy 2003	Morgan and Liker 2006	Brown 2007	Schuh et al. 2008
1. Strong Project Manager	X	X	X	X	X	X		X
2. Specialist Career Path				X	X	X		
3. Workload Leveling			X			X	X	X
4. Responsibility-based Planning and Control				X	X	X	X	X
5. Cross-project Knowledge Transfer							X	X
6. Simultaneous Engineering	X	X	X			X	X	
7. Supplier Integration	X		X			X		
8. Product Variety Management						X		X
9. Rapid Prototyping, Simulation and Testing							X	X
10. Process Standardization						X	X	X
11. Set-based Engineering				X	X	X	X	X

idea is to establish the role of an experienced project manager who leads the development projects from concept definition to market, and is ultimately responsible for delivering value to the customer (Morgan and Liker, 2006).

The use of project managers in product development is not unusual (Armstrong, 2001). The tasks of a strong project manager, however, go beyond the sole management and integration of functions which are the main responsibilities of a traditional PD project manager (Womack et al., 1990). At Toyota, at the beginning of a project, the Chief Engineer conducts extensive research and analyzes competitor products in order to understand what the customer values (Ballé and Ballé, 2005; Morgan and Liker, 2006). After the customer requirements have been documented, it is the role of the Chief Engineer as the "voice of the customer" to translate the product definition into well-aligned goals for the different functions involved (Haque and James-Moore, 2004; Ward et al., 2007). This includes not only the definition of project milestones and the negotiation of deadlines with development engineers, but also the derivation of clear cost and performance targets for particular components.

The adherence to the project schedule, cost, and performance targets set at the beginning of the project is continuously checked by the strong project manager during the actual design phase (Schuh et al., 2007). Moreover, the strong project manager is strongly involved in the development of the technical details. Ideally, he is the most experienced and knowledgeable engineer on the project, makes major component choices, and chooses the technology used for the product (Karlsson and Ahlstrom, 1996; Kennedy, 2003; Morgan and Liker, 2006; Oppenheim, 2004; Sobek et al., 1999; Ward et al., 2007).

Specialist Career Path

Considering the complexity of problems that have to be solved in the course of a PD project, it is indispensable to make use of technical specialists with dedicated expertise in a particular field. To develop this expertise and foster the exchange of knowledge among specialists of the same domain, engineers are traditionally assigned to functional divisions. The functions serve as schools that continuously gather knowledge and best practices and teach it to their members (Haque and James-Moore, 2004; Ward et al., 2007; Womack and Jones, 1994).

In traditional organizations, engineers often do not spend a long period of time in the same functional division. Career paths are built in a way that with promotions, technical focus gets increasingly substituted by general management and administrative tasks. It has been observed that engineers in Lean companies tend to stay within their technical position for a much longer period of time than engineers in traditional companies (Ward et al., 2007). Furthermore, to give engineers the possibility to gather more experience in their particular functional domain, many Lean companies have introduced designated specialist career paths that promote the development of technical expertise in a field (Schuh et al., 2007). In the literature on human resource management, this concept has become know as the "dual career ladder" (Allen and Katz, 1986), although in practice the dual career ladder concept has shown uneven application and inconsistent results.

One of the companies making strong use of a specialist career path is Toyota. It usually requires a Toyota engineer a minimum of 10 to 12 years before he or she becomes eligible for promotion to a first-level management position (Morgan and Liker, 2006). After a rigorous hiring process, engineers go through a period of intensive on-the-job training that aims to promote technical expertise and a standardized skill set among its engineers. During this time, they are closely supervised by a designated mentor (Ward et al., 2007). Performance and potential areas for improvement are discussed in feedback interviews that are held on a regular basis for six to eight years (Sobek et al., 1998). Based on the level of demonstrated skills and their adherence to standard procedures, engineers then slowly climb up the career ladder (Morgan and Liker, 2006; Ward et al., 2007). These practices help them build the required knowledge base for the system-level problem-solving and continuous improvement activities that are a key part of a Lean PD system.

Workload Leveling

An unleveled workflow is tightly connected with overburdening of employees, a decrease in the quality of PD activities, an increase in lead times, and higher product development costs (Fiore, 2004; Morgan and Liker, 2006; Ward et al., 2007). In the literature on Lean PD a number of practices have been described that focus on leveling the workload of engineers through measures of resource planning and control.

First, it is important to note that different product development projects with timely overlap compete for the same financial, technical, and human resources. When trying to maximize the overall product development performance of an enterprise, it is, therefore, of major importance that their resources be planned on a cross-project basis—a methodology Cusumano and Nobeoka (1998) refer to as multi-project management. To achieve a leveled workload and generate a smooth flow of PD projects, it is generally recommended to stagger projects and launch them in constant intervals (Ward et al., 2007). When determining the exact scheduling of projects, the availability of different functional specialists and their capabilities has to be taken into account. In this context, a particular challenge lies in avoiding inefficiencies through multitasking (Fiore, 2004; Mascitelli, 2007; Smith and Reinertsen, 1997; Ward et al., 2007).

A reliable planning of shared resources is not possible if the duration and resource demand of the single projects are highly unpredictable. Hence, the practices of multi-project management described in the previous paragraph need to be supported by detailed scheduling and capacity planning on the project level. The tasks to be solved by the participating functions need to be clearly prioritized, synchronized, and consistently executed. In order to establish an even flow of the activities within the project, some authors suggest replicating the cadence of project launches of the multi-project level and establishing rhythmic cycles within the projects (Haque and James-Moore, 2004; Oppenheim, 2004; Ward et al., 2007). Since unforeseen events and iterations can cause deviations from schedule, actual and planned capacity utilization have to be compared frequently. If in the course of the product development a bottleneck occurs, resources have to be flexibly adapted. Hence, for a Lean PD system, the availability of flexible, extra capacity is of large importance. Toyota, for example, compensates excess resource demands through a combination of flexible staffing and the use of external satellite companies to which work can be outsourced (Morgan and Liker, 2006).

Responsibility-Based Planning and Control

In general, two approaches can be distinguished for planning and scheduling the detailed activities of a product development project: top-down planning and responsibility-based planning. Using top-down planning, all activities of the project are planned by the project leader or a designated project planner. The engineers who execute the tasks are not involved in the planning process but are assigned detailed tasks with clearly defined, non-negotiable deadlines by their superiors. In contrast to this, in a responsibility-based planning approach, the project leader sets only the major milestones for the project and communicates the corresponding target dates to the engineers. Based on the targets, the engineers detail their particular work streams, estimate their duration, and report to the project leader whether or not the proposed schedule is feasible. Through several iterative loops, the project leader and the engineers negotiate deadlines for critical activities to ensure that goals are realistic but at the same time challenging enough to allow for a short lead-time of the overall project. At Toyota this procedure of breaking higher-level goals down into meaningful lower-level objectives and aligning them across different stakeholders through extensive negotiations is known as Hoshin Kanri (Morgan and Liker, 2006). Once the project leader and the engineer have agreed on a milestone, the engineer is free to choose the starting point of his work and experiment with new approaches as long as he can meet the deadline (Kennedy, 2003; Ward et al., 1995).

In the literature on Lean PD, several authors have argued that responsibility-based planning is superior to top-down planning as it contributes to a higher accountability and motivation of engineers, more robust schedules, higher responsiveness to unexpected events, and a continuous improvement of processes (Kennedy, 2003; Schuh et al., 2007; Ward et al., 2007).

To ensure that the stronger distribution of responsibilities does not go to the detriment of the project's lead time, at Toyota in the course of the project, program status, open issues, and performance to metrics are tracked in frequent project reviews which, equivalent to kanban cards in production, pull the work of the engineers (Ward et al., 2007). Using andon boards and visual management, every project member is given the opportunity to check his own performance to determine if additional efforts are required to achieve a milestone on time (Morgan and Liker, 2006; Ward et al., 2007).

Cross-project Knowledge Transfer

It has been shown that even highly innovative products strongly depend and build upon knowledge of older products. This knowledge, if not appropriately captured, has to be continuously regenerated (Morgan and Liker, 2006; Thomke and Fujimoto, 2000). As an example, Watkins and Clark, studying the design of front and rear auto body closures, found that problems are often repeatedly solved in consecutive projects (Watkins and Clark, 1994).

To avoid the regeneration of knowledge, it is generally recommended that explicit documentation of the best practices and lessons learned of projects take place. In the literature on knowledge management, a vast number of methods and tools for capturing and storing knowledge have been described, ranging from sophisticated web-based repositories to simple checklists. The detailed discussion of all the alternatives with their particular advantages and disadvantages is a separate stream of research and beyond the scope of this study. Here, it should only be noted that, for the viability of knowledge transfer, it is of particular importance that the barriers to enter, retrieve, and update the knowledge be as low as possible. Data should be organized in a clear, logical way so that engineers can quickly review it as they face a particular design task (Brown, 2007). Additionally, the usefulness of a knowledge database strongly depends on how often the data it contains is updated. An organization should have clearly defined processes for capturing insights on both good and bad design practices during the projects. Engineers should be given both sufficient time and an incentive to share their experience with other members of the organization (Morgan and Liker, 2006; Oppenheim, 2004). The accumulated knowledge base should be regularly reviewed, reorganized, and simplified to maintain its usability (Mascitelli, 2007).

At Toyota, for every major part of a vehicle there is a part-specific checklist containing what the company has learned over the years. The checklists list the steps not to be missed during the design process and provide highly detailed, often visual information regarding "good and bad design practices, performance requirements, critical design interfaces, critical to quality characteristics, manufacturing requirements as well as standards that commonize design" (Morgan and Liker, 2006). Engineers use the checklists throughout the project to guide their decision making and facilitate the review of designs. They constantly update the information contained in the checklists and abstract their experience using so-called trade-off curves that graphically describe the governing influence factors determining performance and failure modes of a part (Morgan and Liker, 2006; Ward et al., 2007).

Simultaneous Engineering

In traditional, sequential engineering, product development is conducted in subsequent, mostly independent phases. After the product concept has been developed and evaluated, the single modules are designed, tested, and integrated. Once integration is complete, the system of modules is tested and serves as the basis for the design of production facilities and processes. In contrast to this, in simultaneous or concurrent engineering, the single phases of product development are not conducted one after the other but in an overlapping way (Haque and James-Moore, 2004; Nevins and Whitney, 1989; Sohlenius, 1992). This concurrency of activities offers the potential to significantly reduce the lead-time of the product development project (Karlsson and Ahlstrom, 1996; Sobek et al., 1999; Ward et al., 1995).

In practice, simultaneous engineering is typically implemented in the form of cross-functional teams and meetings. Organizational stakeholders such as manufacturing, quality assurance, and purchasing are integrated in the product development project at an early stage (Karlsson and Ahlstrom, 1996; Sobek et al., 1999). They are involved in discussing the product concept and review design proposals to make sure that the drafts meet the needs of all internal and external stakeholders (Haque and James-Moore, 2004). Furthermore, representatives from manufacturing and assembly work with designers and product engineers to develop production processes and facilities in parallel to the product (Womack et al., 1990). While requiring a higher coordinative effort, this early consideration of abilities and constraints in manufacturing helps to avoid iterations and rework of designs at later points when decisions are already locked-in (Brown, 2007; Karlsson and Ahlstrom, 1996; Liker et al., 1996; Nevins and Whitney, 1989; Susman, 1992).

Toyota, to foster simultaneous engineering in its PD processes, uses two major mechanisms: module development teams (MDT) and the obeya (big room). MDTs are cross-functional teams which are set up for each vehicle subsystem at the beginning of a PD project. Their main task is to negotiate how to achieve the performance characteristics given by the Chief Engineer and resolve key challenges early in the process when there is still a large amount of flexibility. Each of the MDTs is assigned one or more designated simultaneous engineers (SE) who serve as program-dedicated representatives from manufacturing. Furthermore, Toyota has set up special rooms, called obeya, which serve as venues for regular meetings between the chief engineer and the leaders of the functional groups. On the walls of the obeya, the functional engineers post the latest information on the status of the project as well as drafts, simulations, and test results, thereby enhancing cross-functional collaboration (Morgan and Liker, 2006).

Supplier Integration

Traditionally (chiefly in the western world) companies work with a large number of suppliers for every part. Before approaching the suppliers, they define detailed part specifications, invite for tenders and—mainly based on price as a criterion—award the business to a supplier. As Liker et al. (1995) point out, in the case of the automotive industry, this tradition has resulted in a situation with adversarial relationships between automakers and outside suppliers. Automakers have often used their market power to extort low prices from suppliers. Suppliers, in turn, have been reluctant to share inside information with original equipment manufacturers (OEM), fearing that their customers could use this knowledge against them in the bidding process. After being chosen as the supplier for a particular part, they have used inevitable changes in the product development process to raise their initially negotiated price (Liker et al., 1995; Morgan and Liker, 2006; Ward et al., 2007). The process of price negotiation with a large number of suppliers requires a high amount of resources on the part of the OEM, resulting in large purchasing organizations (Fiore, 2004; Liker et al., 1995; Morgan and Liker, 2006).

Companies with a strong emphasis on Lean practices have been found to follow a fundamentally different approach regarding their relationship with suppliers. They usually have a much smaller supplier base with whom they work on a longer-term basis. Key suppliers are integrated into the product development activities at an early stage and work closely with the development engineers of the OEM (Dyer, 2000; MacDuffie et al., 1996; Morgan and Liker, 2006). At Toyota, using pre-sourcing arrangements, key suppliers (typically two or three per part) are already incorporated in the extended product development team during concept stage and actively participate in the design process (Fujimoto, 1999;

Karlsson and Ahlstrom, 1996; Liker et al., 1995; Morgan and Liker, 2006). In order to improve the performance of suppliers and reduce costs, Toyota engineers discuss with the suppliers how their product and development processes can be improved and offer their help to solve issues with designs (Liker et al., 1995; Ward et al., 1995). Furthermore, Toyota constantly hosts several hundred guest or resident engineers who are residing full-time at Toyota's product development department (Liker et al., 1995; Morgan and Liker, 2006).

Despite its close cooperation with suppliers and extensive outsourcing of parts and engineering, Toyota is very careful to not lose critical knowledge and prematurely award business to suppliers who cannot guarantee to deliver the expected quality (Liker et al., 1995; Morgan and Liker, 2006). The strategic importance of parts is carefully evaluated before its development is transferred to suppliers. Development and production of critical parts are not outsourced but kept within the company in order to maintain control (Morgan and Liker, 2006).

Product Variety Management

A large variety of products, components, and parts comes at the cost of larger complexity, higher inefficiencies, and decreased possibilities for using economies of scale throughout the entire product lifecycle (MacDuffie et al., 1996). In order to avoid the drawbacks that are connected with a high variety in products and parts, in the literature on Lean PD several authors have suggested using techniques that can be summarized under the common heading of "product variety management" (Ramdas, 2003). Specifically, authors propose to make use of commodities, reuse parts, and define modular components and product platforms.

First, whenever a part of a product is not perceived as a critical differentiating feature by the customer, can be easily ordered from a catalogue, and cannot be manufactured by the company at a significant cost advantage, it is generally recommended to order the part from a supplier instead of developing and producing the part within the company. Using catalogued parts allows an organization to draw on the experience of suppliers who have specialized in an area and helps to reduce engineering effort and risk (Fiore, 2004; Ward et al., 2007).

Besides making use of commodities in designs, a company should try to reuse product parts among different modules, products, and product families as well as subsequent versions of the same product. Parts should only differ if this is justified by a perceivable value-added for the customer (Ulich, 1995). Toyota, for example, has a carry-over rate, i.e. percent reuse of components from a previous model to the successor, of about two-thirds (Schuh et al., 2007). Toyota is very cautious about introducing new technologies and tries to leverage their proven solutions from existing products as much as possible (Fiore, 2004).

Ordering single components from catalogues and reusing parts from previous products and other subsystems is difficult if the product is highly integrated (Baldwin and Clark, 2000); therefore, the literature on Lean PD generally recommends dividing the products into distinct modules and subassemblies with standardized interfaces. Modules facilitate the redesign of particular parts of the product, allow parallelization of design tasks, improve maintenance issues, reduce complexity, and foster learning and continuous improvement (Fiore, 2004; Haque and James-Moore, 2004; Morgan and Liker, 2006; Smith and Reinertsen, 1997).

To be able to use modules across several product lines and maximize the reuse of parts, a company can furthermore make use of product platforms. Product platforms serve as a carrier for different subassemblies. They allow the combination of modules with standard geometries and interfaces in a way that leads to high flexibility and diversified products while keeping overall part variety low (Meyer and Lehnerd, 1997; Meyer and Utterback, 1993; Morgan and Liker, 2006).

Rapid Prototyping, Simulation and Testing

Considering the large number of iterations that are required for one product development project, an increased speed of problem-solving can decisively shorten time-to-market and have a positive effect on product quality, performance, and organizational learning (Brown, 2007; Smith and Reinertsen, 1997). In this context, authors in the literature on Lean PD have emphasized that methods and technologies supporting fast prototyping, simulation, and testing of designs can significantly contribute to a high-performance product development system. They provide the engineers with quick feedback on ideas, result in a faster convergence of designs, and ensure integration among different modules (Morgan and Liker, 2006; Oppenheim, 2004; Schuh et al., 2007; Thomke and Fujimoto, 2000; Ward et al., 2007).

The traditional way of quickly evaluating designs lies in building physical models and prototypes. It has been pointed out that, to foster well-grounded decisions and avoid problems in later phases, prototypes should be built in early stages of product development (Ward et al., 2007). Using low-cost techniques, mock-ups of products can first be modeled out of foam, foam core, cardboard, or wood to gain fast insights on geometric properties (Ward et al., 2007). Later, the designs are translated into more sophisticated prototypes to check the integration of modules and test the system for failure modes. At Toyota, while the first prototypes are assembled very carefully to check the interfaces of subassemblies, all subsequent prototypes are produced and assembled using Lean Manufacturing techniques (Ballé and Ballé, 2005). As Ward reports, by the consequent application of Lean Manufacturing techniques, the Toyota supplier Delphi in one instance was able to cut times for simulation and tests from weeks and months to 24 hours each (Ward et al., 2007).

In recent years, traditional ways of prototyping have been more and more complemented by advanced digital technologies such as computer-aided modeling, simulation, digital assembly, and 3D prototype printers. The use of these techniques can, if employed appropriately, strongly contribute to identifying and solving problems at a faster rate. Iterations can be run earlier and often at a lower cost than is possible with elaborate, expensive physical prototypes that require a long time to build (Morgan and Liker, 2006; Thomke and Fujimoto, 2000). Moreover, virtual tools such as digital assembly can help identify problems before the program enters prototype phase which can result in a lower number of prototypes needed (Morgan and Liker, 2006).

Process Standardization

While product development projects naturally differ from case to case, it has been found that many tasks required for planning and executing product development are quite consistent across different projects (Fiore, 2004; Morgan and Liker, 2006). To increase product development performance, it is widely recommended to identify these reoccurring tasks and standardize them. Standardization helps to reduce variability, increase efficiency, minimize errors, capture and manage knowledge, and serves as a basis for continuous improvement (Ballé and Ballé, 2005; Morgan and Liker, 2006; Sobek et al., 1999).

From a macro perspective, a very common way of standardizing processes is to predefine a sequence of project milestones in which product development projects within the organization ought to be completed (Liker et al., 1995; Morgan and Liker, 2006). Particularly in combination with other standardized tools for project planning, using blueprints for project planning can contribute to a higher reliability of plans and a better synchronization of functions (Morgan and Liker, 2006). As every project follows the same general order of steps, engineers are able to develop a certain routine and gain a deeper understanding of their role in the overall value stream (Morgan and Liker, 2006). When problems arise during product development, the use of standard processes facilitates more rapid problem diagnosis, root cause analysis, and development of remedial countermeasures (Spear and Brown, 1999). Also, in an organization where multiple projects are conducted at the same time, knowing the sequence in which tasks are completed can strongly facilitate the planning and alignment of shared resources (Morgan and Liker, 2006.

To reduce variety during the execution phase of the PD project individual engineers should be provided with standardized tools and procedures that support them in their creative design efforts (Ballé and Ballé, 2005; Morgan and Liker, 2006). These can range from standardized work instructions and design standards to standardized methods for problem solving. At Toyota, for example, besides standard checklists and trade-off curves, engineers make extensive use of a method called "five whys" that allows them to analyze the root cause to a particular problem (Ballé and Ballé, 2005). Problem solving is supported by special decision matrices (Morgan and Liker, 2006). Additionally, documentation and communication of information is facilitated by the use of dense and highly structured A3-reports (Morgan and Liker, 2006; Ward et al., 2007).

Adherence to standards in many ways constitutes an important part of a Lean PD system; however, as Ward and Kennedy particularly put forward, imposing a large number of standards can quickly lead to overregulation and impair the fourth Lean PD component—responsibility-based planning and control. Since this has negative consequences for organizational learning and innovation, it is important to continuously challenge the standards and make suggestions for their improvement (Morgan and Liker, 2006).

Set-Based Engineering

Set-based engineering, also known as set-based concurrent engineering or set-based design, describes a new paradigm for structuring the process of developing a particular product module.

Normally, at the start of a PD, project engineers develop a small number of alternative concepts for each product module, assess the solutions, and select the most promising one to be pursued in the further product development process. In an iterative process, the selected solution is then refined, tested, and modified until it satisfies the requirements formulated at the beginning, and can be successfully integrated with other modules (Liker et al., 1996; Ward et al., 1995).

Using set-based engineering, a much larger number of possible solutions for each product module is considered at the front-end of the PD process. Instead of quickly narrowing down the set of alternatives, engineers design, test, and analyze multiple solutions for every subsystem in parallel (Morgan and Liker, 2006). Using extensive prototyping and testing, engineers explore failure modes and trade-offs of particular solutions and check for the compatibility with adjacent parts (Ballé and Ballé, 2005; Morgan and Liker, 2006). Only when, based on objective criteria, a solution has been proven to be inferior to other designs, this design is removed from the solution space (Schuh et al., 2007). In this way, the set of alternatives is gradually narrowed down and finally converges to a single solution (Ward et al., 2007). Once the engineers have decided on a particular solution for a design, this solution remains unchanged until start of production unless altering the module is absolutely necessary (Ward et al., 1995).

In the literature on Lean PD, it has been argued that the procedure suggested by set-based engineering is superior to the one used in traditional product development because investing time and resources to explore alternatives early in the project significantly reduces uncertainties and iterations in subsequent phases of the project (Ballé and Ballé, 2005; Sobek et al., 1999). Since changes in design become more costly as the project proceeds towards the start of production, front-loading the product development process instead of iterating in later stages is likely to reduce the overall cost of product development (Kennedy, 2003; Liker et al., 1996; Schuh et al., 2007; Ward et al., 2007). Moreover, modifying a solution late in the product development process causes rework, often affecting the design of adjacent components and, therefore, causing major disruptions in flow (Brown, 2007; Liker et al., 1996; Sobek et al., 1999; Ward et al., 1995; Ward et al., 2007). Especially when capturing and reusing the knowledge that is generated through early in-depth investigations, set-based engineering can possibly find more innovative and robust solutions than the point-based approach (Kennedy, 2003; Sobek et al., 1999; Ward et al., 1995). It should be noted, however, that in the case of complex and costly goods, building a large number of prototypes might be prohibitively expensive, making computer-aided simulations the more viable option.

Interdependencies between the Lean PD Components

In the previous sections, the 11 Lean PD components derived in the first step of the content analysis were presented. In this section we summarize the findings of the second step—the analysis of the component interdependencies. Exhibit 3 displays the cause-effect matrix showing the theoretical qualitative interdependencies between the 11 Lean PD components. The first row and column each contain the 11 Lean PD components, spanning a table of 121 fields. The entries of the table qualitatively describe how the row element and the column element are hypothetically linked. Specifically, each entry details how the component in the row may require the component in the column. As an example, the component Responsibility-Based Planning and Control (column) is thought to contribute to the component Specialist Career Path (row) by enhancing individual learning through higher involvement, accountability and ownership. Vice versa, Responsibility-Based Planning and Control (row) is likely supported by the component Specialist Career Path (column) in the way that engineers have a higher expertise to set their own goals, estimate the time they require for a particular task and are better able to achieve the goals they have defined for themselves.

As explained, the relationships described in Exhibit 3 were derived using two methods. First, links were directly extracted from literature through content analysis. Second, based on our thorough investigation of the components, we hypothesized links for pairs of components where the content analysis yielded

Exhibit 3. Theoretical Qualitative Interdependencies Between the Components of Lean PD

How does component in row require component in column?	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
Strong Project Manager	X	Development of qualified Strong Project Managers, reliable concept development and planning due to help of experienced engineers [27]	Reliable project planning and progression due to reduced over-burdening of engineers, lower waiting times, clear prio-ritization of activities [26]	Reliable project planning and progression through better adherence to schedule and larger motivation; reduced planning efforts [12]	More reliable project planning, cost and time estimation [22]	More reliable project planning and progression due to early integration of manufacturing, parallel development of product and process [17]	More reliable project planning and progression due to early integration, careful outsourcing and high quality of delivered parts	More reliable project planning and progression due to reduced design and testing requirements [16]	More reliable project planning and progression due to early and shorter problem-solving cycles [1]	Faster project planning and better control through standard milestones, tools, documentation and communication [1, 2]	More reliable project planning and progression due to reduced late engineering changes, high robustness of solution [1]
Specialist Career Path	Project manager as role model and mentor; learning through constant design reviews [17]	X	Time for teaching, mentoring and reflection, increased learning through more reliable project runs [26]	Enhancement of learning through higher involvement, accountability and ownership [26]	Enhancement of technical expertise through ever-increasing knowledge-base [17, 22]	Cooperation with internal stakeholders as important competence of product development engineers	Cooperation with suppliers as important competence of product development engineers	Better specialization and faster learning due to clearly separated modules	Increased and faster learning through early and shorter problem-solving cycles [23, 26]	Increased and faster learning through standard process logic, reduced variability through standard tools, and documentation [17]	Increased and faster learning through consideration of wider set of technical solutions [22]
Workload Leveling	High predictability of projects through rigorous project-internal planning and control, clear concept, cross-functional coordination [7, 17, 19]	High availability of functional specialists for flexible planning; less iterations through standard skills, high techn. expertise [17, 22]	X	High predictability of projects through better adherence to schedule, larger motivation [26]	Reduced variability through avoidance of unnecessary steps, iterations and learning	Reduced variability through early integration of manufacturing/ parallel development of product and process [17]	Reduced variability through early integration, careful outsourcing, rigorous testing and fast sourcing process [17]	Reduced variability through reduced design and testing requirements and parallel development of parts due to standard interfaces [7, 19]	Reduced variability through early and shorter problem-solving cycles [23]	Higher acceptance of common processes due to more reliable project runs and less waiting times	Reduced variability through reduced late engineering changes, high robustness of solutions [24]
Responsibility-based Planning and Control	Alignment of sub-goals to customer value; frequent control of adherence to goals and schedule [11]	Technical expertise to set goals, estimate time required and adhere to goals set [24, 26]	Reliable planning of tasks and estimation of durations through clear staggering and prioritization of projects	X	More reliable planning of tasks due to availability of past experience	More reliable planning of tasks due to large amount of interaction with manufacturing	More reliable planning of tasks due to fast sourcing and high quality of delivered parts	Better planning and easier control of tasks due to clearly separated modules	More reliable planning of tasks due to early and shorter problem-solving cycles	Improved planning and control of tasks due to standard tools for design and communication [17]	More reliable planning of tasks due to reduced late engineering changes, high robustness of solutions [14, 24]
Cross-project Knowledge Transfer	Enforcement of use of checklists and knowledge transfer [17, 26]	Higher ability for reflection and documentation of lessons learned [17, 24]	Time for reviewing past project findings before project start, time for reflection and documentation of lessons learned [17, 26]	Higher incentive for using past knowledge due to accountability and ownership	X	Documentation and reuse of knowledge on requirements of and design for manufacturing	Integration of supplier requirements and ratings in documentations	Easier documentation of best practice of structures and designs due to lower part variability and clearly defined interfaces	Generation of objective test data through early and short problem-solving cycles [23]	Better reuse of knowledge due to similarity of subsequent projects and tools employed [17]	Increased rate of knowledge creation and documentation through consideration of wide range of possible solutions [10]
Simultaneous Engineering	Enforcement of early integration and synchronization of product development and manufacturing [12, 22]	Better understanding of engineers for needs of manufacturing [17]	Higher predictability of demand for functional specialists; improved synchronization [17, 18]	Higher incentive for cooperating with manufacturing due to accountability and ownership	Transfer of manufacturing requirements and best practice solutions [17, 22]	X	Early integration of manufacturing requirements in supplier contracts	Reduced complexity of parallel product and process development through standardized modules and interfaces	Early and faster testing and optimization of design for manufacturing and assembly [1, 2]	Better synchronization of product and process development through standard procedures and tools [17, 22]	Earlier and stronger integration of manufacturing through early consideration of different alternatives [24]
Supplier Integration	Enforcement of early integration and synchronization with suppliers [17]	Clear definition of requirements; early identification of problems; mentoring and teaching of suppliers [17]	Reliable deadlines for parts delivery [13]	Higher incentive for integration of suppliers due to accountability and ownership	Documentation of supplier performance, preferred suppliers and their strengths and weaknesses	Improved make-or-buy decision making, precise definition of requirements, mentoring of suppliers in manufacturing strategies [26]	X	Reduced sourcing effort through reuse; clear separation and inter-changeability of modules through standard designs and interfaces [15, 17, 26]	Faster formulation of requirements and early discovery of problems with supplied parts through rapid testing and prototyping [26]	Better integration of suppliers through standard procedure for contracting, partnering and sourcing	Earlier and stronger integration of suppliers through involvement in development of alternatives and frequent communication [17]
Product Variety Management	Enforcement of reuse and modularization due to Strong Project Manager's responsibility for cost and performance [11, 18, 22]	High expertise in dealing with particular part functionality, geometry and interfaces [17, 19]	Time for reviewing past designs and structural best practices; time for communication to increase reuse, define modules	Higher incentive for part reuse and modularization due to accountability and ownership	Availability of knowledge on feasibility of part reuse, module and interface design from past projects [2]	Integration of manufacturing requirements in modules and reuse strategy [17]	Definition of standard designs and interfaces for suppliers; integration of suppliers in module and platform development	X	Higher robustness of parts, modules and platforms through early and fast testing and prototyping [17]	Standardized processes and tools for increasing part reuse and developing modules and platforms [17, 22]	Better understanding of interdependence and higher robustness of parts, modules and platforms [19]
Rapid Prototyping, Simulation and Testing	Coordination of testing and prototyping [12, 17, 18]	Seamless cooperation between designer and testing personnel; testing competence among designers [17, 26]	Availability of qualified testing and prototyping personnel when needed [26]	Autonomous development of test plans; higher incentive for early and intensive testing and prototyping due to ownership	Best practices in testing and prototyping; documentation of failure modes [17, 22]	Use of manufacturing expertise in prototyping and testing; early testing for manufacturing requirements and assembly [17]	Fast sourcing of testing equipment, prototype parts and tooling; rigorous testing conducted by suppliers [13]	Faster testing through reuse and standard designs; independent testing and prototyping through clearly separated modules [15]	X	Systematic and faster testing and prototyping through standard procedures [16]	Development of expertise in testing and prototyping through testing of many alternatives
Process Standardization	Reduced variability in processes through better adherence to schedule; reduced iterations due to clear concept [19]	Better adherence to schedule and linear process steps through reduced iterations	Improved planning through standard process logic, predictable and repeatable processes [17, 18]	Continuously improving standards; higher acceptance of common processes due to involvement of engineers in updating	Gathering of best practice milestones and procedures; best practice standard tools	Reduced variability of processes due to early integration of manufacturing [14]	Reduced variability through early integration, careful outsourcing, rigorous testing and fast sourcing process [17]	Reduced variability in processes through increased reuse, standard designs and interfaces [15]	Reduced variability of processes through early and shorter problem-solving cycles [23]	X	Reduced variability through reduced late engineering changes, high robustness of solutions [24]
Set-based Engineering	Coordination of parallel development and driver for narrowing decisions [18, 22, 26]	Expertise for developing alternative solutions, defining interfaces, weighing pros and cons, choosing and merging alternatives [26]	Time to follow several alternatives in parallel and test them rigorously before narrowing in [24]	Autonomous development of alternatives and accountability for results [24, 26]	Freezing and re-use of design sets from previous projects; generalization of solutions in trade-off curves [22, 26]	Consideration of alternative manufacturing processes; evaluation of alternatives for manufacturability and robustness [17, 22, 26]	Development of alternative solutions and narrowing in by suppliers; frequent communication [13, 17]	Clearly separated modules with standard interfaces to be developed in parallel [24, 26]	Rigorous testing of design sets; narrowing based on profound information base; gathering of knowledge in trade-off curves [22, 24]	High synchronization of parallel processes through standard procedures, tools and documentation [17]	X

no insights on interdependencies (which was the case for 30 of 110 total links specified.) The links identified from literature are shown in Exhibit 3 with the references in square brackets, where the numbers in the brackets correspond to the 27 publications listed in Exhibit 1.

The links or interdependencies in Exhibit 3 represent a potentially rich framework of hypotheses that not only lend themselves to testing, but also provide further insights into the structure and relationships in a Lean PD organization. An interesting example is the case of Set-Based Engineering. It has been identified in a number of different sources as a key practice in Lean PD, but not described generally in relation with the other Lean PD components identified in this study. Because it is has been discussed frequently in other sources, all relationships between it and the other components in Exhibit 3 are drawn from existing references, albeit based to varying degrees on empirical evidence. The nature of the relationships suggests that some of the components are prerequisite to Set-Based Engineering (e.g., Process Standardization, Workload Leveling, Specialist Career Path, Product Variety Management, Rapid Prototyping, Simulation, and Testing, Supplier Integration) because they provide the necessary capacity, tools, or processes to execute Set-Based Engineering as it is described. Other components may not necessarily be prerequisites, but are likely coincident with Set-Based Engineering in the near-term (e.g., Strong Project Manager, Simultaneous Engineering) and over the longer term (e.g., Responsibility-Based Planning and Control, Cross-Project Knowledge Transfer) to support and augment its effectiveness. This illustrates that these components may be interrelated on multiple dimensions and in various ways. The relationships between the components in Exhibit 3 are fully specified (i.e., all fields define relationships), but the nature of those relationships is far from fully explored.

Overall, while in the previous sections the 11 Lean PD components were presented as separated entities, the theoretical analysis of their relationships suggests that they are by no means independent. In fact, as Exhibit 3 shows, it is likely that the components interact with and depend on each other in a variety of ways. Even though the degree to which components are linked differs, our analysis suggests a view of Lean PD as a system of highly interwoven elements which only in their concurrency lead to a stream-lined and cost-efficient product innovation process.

Discussion

In this article we analyzed existing approaches to Lean PD and integrated them into a parsimonious and succinct theory framework. We reviewed frameworks for Lean PD suggested in literature and found existing definitions of Lean PD to vary regarding their focus and terminology. We concluded that currently there is an apparent lack of consensus on the constituent elements of Lean PD systems. To fill this gap, we used content analysis to conduct an in-depth analysis of 27 publications on Lean PD. We extracted a total of 316 quotes describing elements of Lean PD and clustered them into 11 major categories, called Lean PD components. Furthermore, we investigated the theoretical interdependencies between the components we had identified. Both the components and their relationships were described in detail to give insights into the definition of a Lean PD system as proposed in this article.

With our work we make three important contributions to a more consistent description of Lean PD. First, while many of the publications in the area of Lean PD when citing previous work refer to a very limited number of studies, we provide a comprehensive description of the background of the research field and its most important contributors. By giving an overview of the historical development of Lean PD, we point to the underlying dynamics that have induced authors to focus on certain components of a Lean PD system and have ultimately resulted in a high fragmentation of the field. Understanding the history of Lean PD, from our perspective, is essential when trying to advance the field in future research. As the second important contribution, our work integrates existing approaches to Lean PD into a single, coherent framework. Unlike previous approaches, we do not simply present another novel definition of Lean PD. Instead we systematically investigate overlaps between frameworks presented previously and combine them to achieve a robust definition of Lean PD. Due to its integrating nature, our theory framework has the potential to dissolve the current fragmentation of the research field and contribute to a common conception of Lean PD. Third, our work fosters the understanding of Lean PD as a system of highly interwoven, interdependent components. In the past, several authors have emphasized the importance of approaching Lean PD from a systems perspective (Ballé and Ballé, 2005; Morgan, 2002; Sobek et al., 1999). This paper presented a thorough investigation of the theoretical relationships between the components of Lean PD. From our point of view the hypothetical dependencies we derived can serve as a fruitful basis for further studies.

An important caveat in the development of this framework is that we have drawn almost exclusively from literature expressly focused on Lean PD. Lean PD is a new and rapidly evolving area of interest, but it represents only a small fraction of the many interest areas associated with the study of PD systems, and ultimately is empirically linked to a rather narrowly-defined population and small sample. This represents a potential limitation in the scope and completeness of the framework described here. We have tried to include research and theory perspectives from the larger PD research community, but are necessarily limited in the scope of what we can include in this article. A more comprehensive exercise of comparing the Lean PD principles identified in this article with those found in existing literature on PD is appropriate and recommended. We remain convinced that our central premise that a generalized framework for Lean PD practices will ultimately allow expansion of empirical findings and theory remains sound.

Building upon our theoretical analysis presented in this article, we suggest a number of directions for future work. First, we recommend advancing understanding of Lean PD at a component level. As pointed out, Lean PD currently builds on a rather small number of empirical studies that have a strong bias toward practices at the automotive manufacturer Toyota. So far, it remains under-investigated as to what extent the components described in this article are used in companies other than Toyota and whether or not the positive effects observed at Toyota are generalizable. More in-depth case studies in different sectors are required to fully understand potential external contingencies that determine the use and success of specific components. The implementation of the Lean PD components should be studied to identify factors and contingencies leading to their successful implementation.

Second, we urgently call for further empirical research on Lean PD from a systems perspective. In fact, of the component interdependencies displayed in Exhibit 3, only a small number result from systematic empirical study. So far, it is not well understood how the use of particular components affects the effectiveness of others. We believe that a better understanding of the interdependencies between the elements outlined in this article plays an important part when trying to explain the performance of a PD system. The study of the interdependencies between components would also benefit from a wider range of samples. On the one hand, these could replicate the large, complex, medium-volume, medium mix PD environment of firms like Toyota. On the other hand, it would be interesting to deliberately depart from that combination of factors and investigate settings as they can be found in high-volume consumer goods firms or large complex projects such as in defense or public works. As far as we know, there are no existing empirical studies of the implementation of a Lean PD system (comprising the scope of the set of components presented in this framework), apart from those of Toyota and its decades-long evolution of its PD system. Insights gained from the study of component interactions at the system level will be of great help when deriving recommendations on how to implement a Lean PD system in an organizational setting. Since this question has a particularly high relevance for practitioners, we are convinced that future research on Lean PD which assumes a holistic systems perspective can add a great deal of value to the field of innovation management.

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About the Authors

Joern Hoppmann is a research associate and PhD candidate at the Department of Management, Technology, and Economics at the Swiss Federal Institute of Technology (ETH) in Zurich. His research focuses on corporate management of technical innovation. Currently, he investigates the impact of policy incentives on innovation strategies in the renewable energy sector.

Eric Rebentisch, PhD, is a research associate at the Massachusetts Institute of Technology, with a focus on developing and managing core product realization and organizational learning capabilities in complex socio-technical systems. He leads the Lean Enterprise Product Development research effort in the Lean Advancement Initiative at MIT.

Uwe Dombrowski is a professor at the Technische Universität Braunschweig and executive director of the Institute for Production Management and Enterprise Research (IFU). After studying Mechanical Engineering in Hamburg and Hannover, Germany, and receiving his doctorate from the Universität Hannover in 1987, he has been holding leading positions in the medical technology industry as well as in the automobile sector for 12 years.

Thimo Zahn is a research assistant and PhD student at the Institute for Production Management and Enterprise Research of the Technische Universität Braunschweig, Germany. Before working for the IFU, he has studied Mechanical Engineering at the Universität Hannover, Germany, and at the University of Strathclyde, Glasgow, UK.

Contact: Joern Hoppmann, ETH Zurich, Phone: +41-76-232-62-36; jhoppmann@ethz.ch