New Perspectives in the Quest for Unification of 'Lean' with Traditional Engineering Design Methodology

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Abstract. In an increasingly competitive business world, engineering companies need to improve their capability in developing products that offer high value to customers. In this connection, the *Toyota Product Development System*—commonly referred to as 'Lean Product Development'—is a benchmark for effective, new practices across industries. *Lean* contains many of the same elements as *traditional* engineering design methodologies, developed in the 1970-80s, which describe systematic design and engineering processes. However, the former differs through its philosophical nature—rather than being a methodology or tool—as well as its focus on increasing effectiveness through waste reduction.

In this paper, a literature review of the traditional, systematic product engineering/development methodologies and the more recent lean concept is conducted. Both approaches are analyzed, providing a discussion as to what extent traditional methodologies include elements of lean-thinking and to what extent the associated product engineering processes are lean.

Keywords: product development, lean, design methods research.

1 Introduction

Nowadays, engineering companies operate more and more globally in increasingly competitive markets. Outsourcing of production and algorithmic engineering tasks to so-called low-cost countries is an obvious countermeasure to increase company benefits in terms of cost reduction; however, this does not guarantee long-term competitiveness. The only permanent solution is to improve a firm's capability in inventing, developing, and producing innovative, new products that provide high value to customers. In addition, companies need to launch new products earlier than their competitors—before new technology emerges or the market changes. These challenges raise the need for more effective engineering design methodologies for developing and bringing valid, new products to the market place. To establish a basis for effective and efficient new-product development (NPD) strategies, it is necessary to understand their origin and evolution by considering the history and the context in which these methodologies have been developed.

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Traditional methodologies, developed in 1970-80s, describe processes to systematically design and engineer a product [5-7], [14], [19-20], [23]. More recently, in the context of effectiveness in manufacturing and product development, Toyota's way of solving engineering problems is often referred to as the benchmark. Multiple researchers have studied Toyota's Product Development System (TPDS), commonly denoted Lean Product Development (LPD), concluding that Toyota's practices are superior to any other firm with regard to productivity in NPD [8-10], [21]. The lean concept—whose primary goals are to reduce waste, time-to-market, and cost while improving quality—has more recently been applied to the process of solving design and engineering problems in product development (PD). It seems that many of the elements found in traditional PD are applied under a new terminology in LPD, but with a somewhat different focus. While traditional PD provides specific, detailed step-by-step guidance to designers and engineers, LPD represents more a mind-set with basis in a set of principles, focusing on the entire system and its practices.

In the following, a literature review of the traditional, systematic PD methodologies and the more recent LPD concept is conducted. Both approaches will be systematically analyzed at detail level, providing a discussion as to what extent traditional methodologies include lean-thinking and to what extent the processes are lean. In this context, the main research questions are: What is new about lean? What does the lean notion bring to NPD—and what is the origin of the methods employed? What is lean about traditional product engineering—and what are the differences, the commonalities and the complementary attributes of traditional and lean methodologies?

2 Traditional Product Development Methodology

Renowned researchers as Rodenacker [19], Pahl and Beitz [14], Hubka [7], Roth [20], and several others, describe methodologies for PD and engineering, developed in the 1970s and 80s, guiding designers and engineers to systematically find solutions to technical problems. Their aim is to provide a methodology to design, engineer and develop desirable solutions that satisfy a set of requirements. However, these methodologies are not the first approaches for systematic engineering and PD. The origin of systematic engineering methods is back in the 1940s [15], [17], and are developed from system theory, machine elements, and product specific approaches. In the development to follow, the PD research community was concerned with increasing the number of engineering principles within the framework of an increasingly structured engineering process, which was divided into different phases (e.g. VDI 2221 [25]). The classical approaches mentioned in the beginning of this section are benchmarks in this context, representing the so-called traditional PD methodology. These methodologies have been adapted to trends and state-of-the-art during the last few decades, for example axiomatic designs [16], [22], product structuring in modules, platforms, and architectures [15], [25], or stronger focus on customization and the whole product life-cycle, while the PD-phases remained essentially the same.

All the above-mentioned authors more or less describe a holistic approach to engineering design; each one providing an individual contribution. In addition, everyone uses the same main structure to develop a product, which can be summarized through the following phases: At first, the main task has to be defined, including in-depth understanding of the problem, which is defined in a requirement list. Then the problem is abstracted into 'black-boxes' [7] or functions, which are decomposed to more abstract sub-functions. In the next phase, different principal solutions are combined to establish (several) concepts. After an evaluation the most promising concepts are chosen for further work. Then, the preliminary layout or the basic product structure is defined, followed by elaboration of the detailed solution, which includes all design features, bill of materials, production methods, etc. All the examined approaches introduced a well-defined engineering methodology, guiding product engineers through the process step by step. The primary emphasis is on tasks required to find solutions to technical problems at design and engineering levels; ones that are driven by engineering excellence rather than process efficiency and cost.

3 Lean Product Development

The TPDS is the main source to what many, right or wrong, consider synonymous with so-called LPD. The concept emerged in the mid-1990s and has its origin in lean manufacturing, starting with the Lean Automotive Factory and evolving into the Lean Factory with emphasis on cost reduction, quality improvement, and delivery [8-10], [12], [24], using a system perspective. Based on an excessive study of TPDS, Morgan and Liker [13] introduced 13 lean principles within the dimensions of process, technology and people. The process-principles are the most interesting ones in terms of the contents of this paper, since the two other dimensions touch more on factors in execution environments outside product engineering. The primary objectives of LPD are to minimize waste, improve quality, reduce time-to-market and cost, all driven by the desire to create value to the customer. Here value may be characterized as any activity that transforms a new product design in a way that the customer is both aware of it and willing to pay for [10]. While waste is easy to detect in manufacturing (visible, physical objects), separating value from waste is more difficult in PD since the work-product is information and there are no physical objects to which value can be assigned. In general, waste can be divided into two categories. Type 1 waste includes activities that do not create value that the customer is aware of, but is still necessary to enable value generation (e.g. administration, coordination, testing, validation, checks, etc.). Type 2 waste is pure waste that does not create any value (e.g. defects, waiting, underutilization of people, etc.).

An important part of the lean philosophy is learning and continuous improvement [13]. Based on the Deming-Cycle [11] improvements and iterations are done continuously in small steps, aiming to reach the ultimate goal of a perfect solution by following a learning-spiral with each cycle closer to the target than the previous one. Although these iterations could be considered waste (type 1) at micro-process level, they are necessary to maximize the value of the overall outcome seen in a system perspective. In addition, by capturing knowledge for later reuse the learning cycle is a source of organizational learning, providing strategic value for the company. In the lean literature, the learning cycle is called PDCA-cycle (Plan, Do, Check, Act) [21] or LAMDA-cycle (Look, Ask, Model, Discuss, Act) [22]. In the first step (Look) the problem is observed and data are collected. Then, it has to be checked what is known about the problem and why this problem exists. Following, a model (prototype, sketch, etc.) to support articulate thinking is established. As the fourth step (Discuss), the problem and possible solutions are discussed with experts, and finally the solution is implemented (Act). In the quest for perfection, the cycle does not stop here but restarts from the first step again; this time at a higher level of knowledge. In the LPD philosophy, knowledge is effectively captured and communicated using 'knowledge-briefs' [8], or so-called A3 reports [21] named by the paper size format used, aiming to visualize problem, goal, process, and solution, and risk elements in a standardized form, depending on the application and problem formulation.

One methodology, often referred in the context of LPD is the so-called set-based concurrent engineering (SBCE) [10], [12]. In contrast to a single (point-based) approach, multiple alternatives are explored in parallel and systematically narrowed down through analysis and testing. Within the set of concepts, one is a proven no-risk alternative concept that can be selected as a fall-back in case the others do not succeed. The weaker concepts are successively 'killed' on the way, following a 'survival-of-the- fittest' strategy. Lastly, only the best and most robust solution that fulfills all requirements remains, hence increasing the opportunity for innovation while reducing risk and development time. SBCE is a method aimed at frontloading resources to reduce late and expensive design iterations.

In summary, LPD it is not just a methodology for engineers, it is a way of working, organizing, and making the PD processes more effective, considering both engineering and product management (PM) problems at engineering and management levels.

4 Comparison of Traditional Product Development and Lean Product Development

It appears that traditional PD and LPD cannot be directly compared to each other, since their overall goals are different. Traditional PD describes a systematic approach of well-defined steps, explaining engineers what to do to create a product that solves a given (technical) problem. LPD, on the other hand, introduces a way to make engineering processes more effective to improve the outcome for a company with value being the driver. It describes how processes have to be done to make a company more competitive by pulling value from customers and up the value chain. Lean is more a philosophy and a mind-set, rather than a detailed methodology to solve engineering problems [27]. Hence, traditional PD explains which steps have to be conducted and what has to be done in these steps, whereas LPD describes the working philosophy around the PD process. However, LPD and traditional PD are not contradictory in any respect. It is possible to apply the lean principles to (all) known engineering methods defined in traditional PD. Lean complements traditional methods by including managerial factors such as effectiveness (e.g. short time-to-market) and waste reduction (e.g. people, money, rework). Table 1 summarizes some key characteristics of both.

Table 1. Characteristics of Traditional Product Development and Lean Product Development

Goals of Traditional Product Development	Goals of Lean Product Development
Gives specific 'work instructions' to mainly engineers at detail level	Gives visionary and directional strategies for the entire company at system level with PD being the core component
Methodology that provides engineers with tools for solving a wide range of technical problems, and developing and designing products	A company-wide PD system aimed at maximizing value to the customer or user, within the constraints of value to other stakeholders [1]
Focusing on developing the best technical solution (high quality) with basis in engineering excellence	Focusing on using an effective process to develop an overall optimal (customer) solution from a system perspective, including operational and strategic management
Use of knowledge and ideas to create solutions for technical problems	Effective capturing and reuse of knowledge and ideas for increased learning, and to develop solutions with highest possible value in the eyes of the customer
Can solve unknown problems and improve existing products; i.e., offering methodologies for both	Strong basis in known processes with predictable outcome (continuous improvement), minimizing technical risk within PD, i.e. after program definition
Follows parallel or sequential processes, aiming to solve the task as well as possible	Follows parallel processes, aiming to solve the task fast with effective use of resources

In the following, traditional PD will be examined with regard to lean elements in order to answer the following question: In which way are traditional PD approaches *lean*? Six different approaches in the category of traditional PD methodologies and one approach of integrated PD—ones that are commonly referred as benchmarks in traditional PD—are analyzed in the context of lean. The findings are summarized in Table 2, which relates a set of lean principles to the reviewed approaches of traditional PD. The lean 'principles' chosen here represent a broad selection of lean components, which are based on the ones introduced by Morgan and Liker [13] and adapted to the scope of this paper. Notice that if a lean component is indicated with an 'x' it is a part of the traditional PD approach, and vice-versa.

Rodenacker's [19] approach is one of the early ones in systematic engineering design, with the basic approach still being applied in methodologies today. Rodenacker aims to find solutions for the cause-effect relations stepwise through logical, physical, and structural working principles. He uses a learning cycle similar to PDCA with the steps: information retrieval, information processing, information output, and checking. Capture, reuse and extension of knowledge all are part of Rodenacker's approach, which are important for continuous improvement.

Tjalve's [23] contribution to the design methodology is mainly form variation. Product solutions and alternatives are developed by systematically varying size, number, structure and shape of the design elements. Tjalve uses a learning cycle, called 'product synthesis', similar to lean. He proposes that the criteria vary from phase to phase and have an increasing number of details, based on details from the former step. This reflects the lean principles continuous learning and improvement.

Pahl and Beitz [14] provide a linear, holistic, systematic engineering design process to help design engineers find solutions for products by the use of different tools. They suggest that a PD methodology should save time, reduce work load, speed-up understanding and help maintain active interest. Further, they want the different functions concerned with development of a product to collaborate early. Problems should be detected early and clearly defined in the requirement list together with customer needs. Pahl and Beitz refer to a learning cycle, similar to the LAMDA cycle: confrontation, information, definition, creation, evaluation, decision, solution. They interpret the design process as a dynamic control process that continues until the information (content) has reached a level for optimum solution. Here it should be noted that many lean approaches follow the same strategy.

Roth [20] introduces design catalogs for engineers. 'Effects', 'effect owners', materials, etc. are systematically structured in catalogs, which make knowledge capture and reuse simple, providing the design engineers a set of standard solutions and recommendations. Roth states that it is important to define the correct problem statement early and to attack problems at the root cause. He does not explicitly use expressions such *customer* or *customer value*, which are important drivers within LPD. However, customer (value) may still be considered as part of his approach since customer satisfaction is mandatory for the success of a product. Roth applies engineering catalogs, which is essentially similar to the knowledge-brief approach [8], [21] within lean. Experiences, standards, and former product solutions can be documented in a visual engineering-friendly way by both approaches. The catalogs, which give fast and clear overview of alternatives, represent a knowledge-based approach to product development. Catalogs can be adapted to the design process of a certain company, and can also be extended. An additional core component of lean is the use of standardization and checklists. For instance, standard tables (and check lists) are used for the gathering of requirements, and these can be adjusted and extended to meet new challenges. In LPD a similar approach is employed by alternative concepts such as *house of quality* and *quality function deployment* (QFD).

Ehrlenspiel [5] discusses the influence of engineering design on product costs, including life-cycle costs. He proposes a number of opportunities to reduce product cost by correct selection of design features, production methods, materials, and good collaboration between different departments inside a company. Cost reduction opportunities lie in standardization of products, which is lean, by for instance using modular product concepts with standard parts or assemblies and customer-specific adaption of parts and assemblies. Ehrlenspiel uses *value analysis* to identify unnecessary costs, aiming to determine which product functions are absolutely necessary to accommodate the task that has to be accommodated to satisfy the customer, which can be associated with reduction of waste, meaning *lean design*. This methodology is also consistent with *value engineering*, which was developed during World War II [27]. Further, Ehrlenspiel encourages close communication between teams and short lines of communication, which supports the pull concept in lean. However, his approach is a more specific approach, guiding engineers to use cost reduction methods in detail, whereas LPD to a more extent approaches system problems.

Hubka et. al. [7] introduce a theory for technical systems, which needs to have transformations (functions), organs (e.g. functional interfaces) and parts (components), where the organs represent the link between two components or one component and the user. Hubka proposes a kind of SBCE; several concepts, which are determined after each design phase, are developed in parallel up to a certain detail level and evaluated. Concepts that are strong enough are carried forward. The evaluation at the end of each phase is based on the status, the experience and learning of previous work, and the customer specifications. This resembles the lean principles of continuous learning, reuse of knowledge, and focus on customer value.

Hein et al. [6] introduce one approach that considers PD in a broader perspective, so-called integrated product development (IPD). This is a more holistic approach that includes engineering design, production, marketing, and organization. IPD seeks to integrate methodologies used in different departments of a company toward common goals, procedures, and attitudes. The customer is of key importance, since s/he ultimately decides if the product becomes a success or not. Hein points out that the market is getting more competitive, which requires shorter development time, less production costs, and fast and continuous implementation of new technology for active adaption and renewal of today's products. Focus is not just on the product itself, but the entire execution environment, which is necessary to make the product successful in the market place. Hence, IPD makes a step forward from pure engineering design methodology in the direction of LPD and product management (PM).

Table 2. Lean Elements in Traditional Product Development Methodology (Legend: - not mentioned; (x) implicitly mentioned; x mentioned)

Lean Principle	Ro-den-acker	Tjalve	Pahl, Beitz	Roth	Ehr-len-spiel	Hubka	Hein
Continuous control of requirements	-	x	x	x	(x)	x	x
Front load of the PD process	-	-	x	x	x	-	x
Understanding the customer	-	(x)	x	-	x	x	x
Integrate customer and supplier in complete development	-	-	-	-	-	-	-
Parallel processes	-	x	-	-	(x)	x	x
Increase standardization, reduce variation	-	x	x	x	x	x	(x)
Continuous improvement of product	x	(x)	x	x	x	x	x
Continuous improvement of process	(x)	-	x	-	-	-	x
Capturing and reuse of knowledge and experience	x	(x)	x	x	(x)	(x)	x
Capturing past knowledge in checklists	(x)	-	-	x	x	(x)	-
Short and precise knowledge capture	-	-	-	x	-	-	(x)
Early include all different departments	-	-	(x)	(x)	x	-	x
Learning Cycle	x	x	x	(x)	x	x	x
Set-based concurrent engineering	-	-	-	(x)	-	x	-
Solving the roots of problems	(x)	-	x	x	x	-	x

This literature review shows that many elements of the LPD concept have been developed under different headings many years before the term lean was coined in the Western PD vocabulary. Learning cycles, knowledge capture and reuse, continuous improvements, and customer value all have been elements of the product engineering literature for several decades. What is new, associated with lean, however, is its strong focus on effectiveness and waste elimination. Hence, traditional PD methodology delivers engineering tools for development of high-quality products, whereas LPD in addition targets effectiveness.

5 Product Development, Product Management and Lean Product Development in a Historical Perspective

In the section above it has been shown that many elements of LPD have their origin from the traditional product design and engineering research community. LPD does reuse traditional approaches to a great extent, applying a different terminology in many cases. Moreover, basic engineering methodology is not part of the lean literature, which rather represents a holistic approach to improve the PD productivity. Some of this may be explained by the historical development of PD or LPD. Figure 1 shows a principal interpretation of historical progress of PD, PM and LPD literature, illustrating the development of the three fields and an increased overlap towards right.

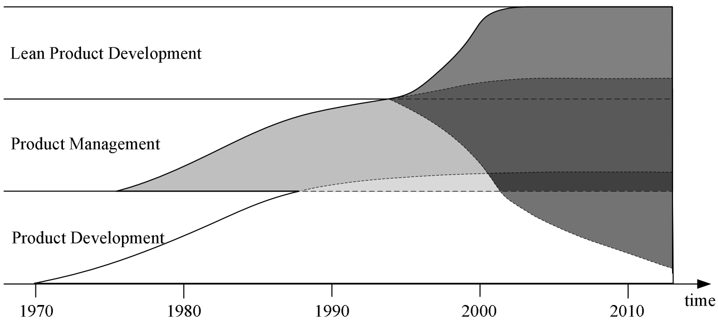

Fig. 1. Development of traditional PD, PM and LPD literature

First, traditional PD started out as a research field in the 1970s, describing methodologies to systematically solve engineering problems and develop advanced products.

Later, throughout the 1980s and 1990s, the amount of PM research increased gradually. In PM, approaches to improve financial performance, innovation, differentiation and new-products' success in the market are introduced as well a holistic business view of marked, product and production in integrated PD [6]. Cooper [2-3], for instance, introduced strategies for successfully driving products to market, like product and technology strategies, portfolio management, and stage gate processes. PM and PD complement each other, since both are important to successfully create and deliver the right product but from different perspectives. This may be illustrated by the two approaches increasingly overlapping each other.

In the late 1990s, yet another approach, namely LPD, emerged from (US automotive) companies' need of being competitive in a global market. Supplementary to the other two approaches, lean puts emphasis on customer, value, waste reduction, and increased effectiveness primarily with basis in the engineering perspective. Lean methods can be applied to—and are becoming increasingly part of—both PM and PD, as symbolized by the overlapping shaded areas. For instance, Cooper [4] realized several of the problems associated with the PM perspective that forms the basis for the classical stage-gate process, and updated his view towards a more process-driven organization, introducing 5-6 concepts directly from LPD.

Today's strong focus on lean methods can be explained through increasing market pressure, forcing companies to reduce time-to-marked and cost while improving innovation. This means that the competitive frontiers drift from, say, engineering excellence and workmanship towards efficiency of process, multi-disciplinary teams, collaboration, supplier integration, networks, knowledge management, organizational learning etc. In this respect, LPD seems to be an important strategy for bridging the gap between traditional engineering-oriented PD and more business-oriented PM.

6 Conclusions

This review and discussion helps to better understand the differences of PD approaches and their historical development. The results show that many of the core elements in LPD have their roots in traditional PD, but under different names and headings. It appears that several classical methods have been reborn under a new common terminology called *lean*. Lean has its origin—or should we say rebirth—in Japan, and was brought into the context of product development by US researchers [8-10], [12-13], [24], [26]; in many cases—purposely or accidentally—not fully considering the methods' original references in the design and engineering community. The good thing about this is that the new 'wrapping' helps bring the methods out to a greater community outside the academic world, including practical engineers, managers and CEOs, boosted by popularization of an approach to an outermost important challenge for many of today's companies: NPD performance.

Nevertheless there are new elements in LPD. LPD adds effectiveness, waste reduction and competiveness to the traditional approaches and makes them evolve and adapt them to today's competitive challenges. It is also demonstrated that the lean concept, when applied to PD, to some extent fills the gap between traditional product engineering (in the engineering community) focusing on micro-processes, and product innovation management (in business-economics community) focusing on macro-processes. To be successful in the marketplace, a combination of both traditional, PM, and LPD appears to be a good approach, applying both the engineering guidance of traditional PD and making processes effective by LPD.

Some very interesting questions in this context are: How did Toyota develop a lean culture and from whom did they adopt their methodology; and how did US and European companies develop the revolutionary products and technologies that have served as a fundamental pillar of productivity growth in the 20th century, decades before the notions 'lean' and 'lean product development' were coined?

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