State-of-the-art in Lean Design Engineering; a Literature Review on White Collar Lean

Abstract

Lean is usually understood to be associated with the 'operations' of a manufacturing enterprise. However, there is growing awareness that Lean principles may be readily transferred to the service sector as well as to knowledge-based activities such as engineering design. To investigate this possibility, the study described in this paper has systematically reviewed the literature to establish the state-of-the-art on Lean in new product development. The findings confirm the view that Lean can be beneficially applied away from the factory; that an understanding and definition of value is key to success; that a set-based (or Toyota methodology) approach to design is favoured together with the strong leadership of a Chief Engineer; and that the successful implementation of Lean requires organisation-wide changes to systems, practices and behaviour. On this basis we feel that this review paper provides a usefull platform for further research in this topic.

1. Introduction

Lean manufacturing (Womack et al, 1990; Cusumano, 1994; Womack and Jones, 1996; James-Moore, 1997; Hines, 2004) is emerging as the dominant paradigm for the design of current UK manufacturing operations. Some see the origins of Lean as a Japanese response to the oil crisis of 1973, examples being Schonberger (1982) who wrote his book 'Nine Hidden Lessons in Simplicity' after a study of the Kawasaki production system, and Womack et al (1990) who wrote 'The Machine that Changed the World' following an international study of motor vehicle manufacturing in which the superiority of the Toyota Production System became clear. Many characteristics of Lean manufacturing are however, clearly evident in the work of Henry Ford (See: My Life and Work, 1922; Today and Tomorrow, 1926). At both his Highland Park and River Rouge plants, Ford demonstrated the essential need to focus on activities that are of service (a value proposition) to the customer and reduce wastes of materials, time and motion, wherever possible. The value of the Lean paradigm to the success of manufacturing is without question, whether we base this claim on the success of 'Fordism' in the 20th century or the Toyota Production System and its derivatives in the 21st Century.

Lean is usually understood to be relevant to the 'operations' of a manufacturing enterprise, meaning those processes associated with material supply, component production, and delivery of products and services to the customer. It is claimed by Womack (1996) and others that 'Lean thinking' can be applied to great effect outside manufacturing operations, although examples of this such as applications in service-based enterprises are relatively rare. This is not to suggest that there is some inherent limitation with the Lean paradigm in this context, but it may be that since international comparisons of manufacturing performance are often easier and waste is more visible in factories, improved practices are more readily transferred around the world. Clearly, the application of Lean principles in the service sector represents an opportunity for improvements in competitiveness. Knowledge-based activities such as design, New Product Introduction (NPI), engineering and Product Development (PD) are areas within an enterprise where the potential benefits from the adoption of Lean principles may be significant. To investigate this possibility, the research described in this paper has been focused on the application of Lean principles to these 'white collar' areas that are away from the factory floor.

The study described in this paper has taken the form of a systematic literature review. The methodology consisted of identifying relevant databases of publications, searching these using a wide range of key words and phrases associated with Lean, new product introduction, design, development and engineering; and then reviewing each article identified. From these reviews it was possible to compile a set of key findings in which the literature is consistent and also a set of key issues where questions remain unanswered or where the literature is contradictory. By establishing these findings and issues, this paper provides a state-of-the-art review of work on this topic and so provides a platform for more detailed case-based work to improve the understanding of Lean thinking in design-related activities.

This paper is structured as follows. First, the context of this study is further explained. Then the research methods are described and the initial results of the search for relevant literature are summarised. The paper then presents the analysis of the literature and the key findings and issues. Finally, the results of this analysis are summarised and conclusions drawn.

2. Background: The industrial context

Manufacturing is strategically important to the UK economy. Aerospace, for example, provides 675,000 jobs, £13 billion of exports, and is frequently a leader in the adoption of new technologies and practices. However, many UK manufacturers face an increasing range of business pressures which either impact directly on manufacturing operations, such as competition from low cost economies, or are an indirect consequence of pressures on the whole enterprise. To remain competitive UK companies are responding in a number of ways. At the level of the enterprise, and consistent with the Government's manufacturing strategy (DTI, 2002; DTI, 2004), there is an increasing focus on innovative, high value and highly skilled activities. This leads to an emphasis on enhancing the design and development capability within organisations, yet within these non-production functions as with manufacturing, the pressures from international competition have also increased dramatically in recent years. Indeed it is argued by Haque (2003) that the continuing existence of a design capability within the UK requires improvements in effectiveness and efficiency.

There are consequently initiatives to improve enterprise wide productivity in the UK. Increasing productivity has universal appeal to any western manufacturer faced with increasingly intense global competition (Lewis, 2000). Within manufacturing operations there continues to be a strong emphasis on adopting Lean techniques (Womack et al, 1990; Cusumano, 1994; Womack and Jones, 1996; James-Moore, 1997; Hines, 2004). The synthesis of Lean manufacturing was provided by the researchers on the International Motor Vehicle Programme of the Massachusetts Institute of Technology, described by Womack et al (1990) in their book 'The Machine that Changed the World'. The term 'Lean' was however more widely popularised by the later publication 'Lean Thinking' (Womack and Jones, 1996). In this paper, Lean thinking, Lean principles and related concepts will often be referred to simply as 'Lean'.

Modern references to Lean have variations in content and perspective. Western companies tend to focus on Lean through the application of tools and techniques, whereas their Japanese counterparts talk of philosophy and culture. The philosophical perspective is a multi-dimensional approach "affecting the entire organisation in every function" (Scaffede, 2002) and encompassing "a wide variety of management practices, including just-in-time, quality systems, work teams, cellular manufacturing, supplier management, etc. in an integrated system" (Shah and Ward 2003). Whatever the perspective, the elimination of waste is the principle that has traditionally been at the heart of the Lean approach (Ohno 1988, Womack and Jones 1990, Papadopoulou et al 2005). Ohno (1988) identified seven forms of waste although in practice, the most frequently cited of these is excess inventory. Lean manufacture discourages holding excessive levels of inventory as this is felt to be a wasteful and expensive response to operational problems that has the effect of hiding the real causes of these problems. Reducing inventory is recommended as this will expose the problems and forcing the underlying causes to be addressed (Bodek 2002).

The case for Lean is usually made by considering the remarkable commercial performance of Toyota whose profits at the end of 2003 were $8.3 billion. This was greater than the combined profit of GM, Chrysler and Ford, and for the first time ever Toyota became one of the top three car sellers in the US (Liker, 2004). In 2006 Toyota is likely to reach the number 1 position. Similarly Womack et al (2001) provide evidence of benefits of Lean achieved in a number of companies across the world that operate in very different market sectors from Toyota, such as Porsche and Pratt and Whitney. However, achieving such improvements is often difficult (Scaffede, 2002) and there is clear evidence in the literature that the benefits of Lean can not be realised simply by adopting a few tools and techniques. In the case of Toyota, Cleveland (2006) notes that the Toyota Product Development System has been key to their success and claims that Toyota's Lean manufacturing system is actually an extension of their product development philosophy and not the reverse. Conversely, most Western manufacturers are focusing their Lean initiatives at operations with (as this paper will demonstrate) few attempts to adopt Lean in design-related activities.

Following the example of Toyota, there appears to be a significant opportunity to benefit from the adoption of Lean in product design, engineering and development. Indeed, there may actually be few practical alternatives and the potential benefits of Lean in design-related activities are certainly worthy of careful exploration. Therefore, the purpose of this paper is to provide an up-to-date review of Lean (in its widest interpretation) and its application to the processes of Product Development (PD) within manufacturing enterprises.

3. Research Programme

3.1 Aim, scope and research questions

The aim of the research presented in this paper was to seek detailed descriptions of the application of Lean principles to product design, engineering and development. To achieve this, this study has carried out a systematic review of literature in this field. The scope was limited to publications dealing with the processes associated with Product Development (PD). This means that studies of the application of Lean to other types of 'white collar' work, such as sales order processing for example, have not been included. Similarly only descriptive articles reporting on real examples and cases have been considered so that purely theoretical, conceptual and abstract works have been excluded. An example of a publication that is clearly within the scope of this review process is that of McManus (2005) in which the author reviews the result of applying Lean engineering techniques to existing aerospace programmes.

Our initial approach to this study has been to consider the questions that a typical practitioner might pose when considering the application of Lean to product design, engineering and development. These were considered to be:

- *What is commonly meant by the term Lean?*
- *How is Lean commonly applied?*
- *Are there any apparent limitations to the application?*
- *Where are the best examples of good practice?*

The purpose of these questions was to guide the search although the authors were mindful that the literature may not be sufficiently developed to allow all these questions be addressed with full rigour. Hence, it was not expected that each should necessarily lead to a key finding.

3.2 Search strategy

The search strategy was developed by first identifying the relevant data sources, time frame and key words. Initially a very broad selection of databases was identified covering journals, conference proceedings, books, and articles from trade journals. These included Compendex, Inspec and Emerald, along with the more traditional library cataloguing systems. These databases provide access to a wide variety of publications such as the Journal of Engineering Design, International Journal of Automotive Technology, Software and Quality Journal, Journal of Product Innovation, Journal of Construction Engineering and Management, Proceedings of the Institute of Mechanical Engineers, Engineering Technology and Systems Engineering.

In order to restrict the search to more recent publications, the time frame for this study was initially chosen to include only literature published between 1999 and 2005. However, as the research progressed this was extended, firstly by widening the search criteria to include publications before 1999 and secondly by checking relevant publications cited in the literature that had already been identified by the original search.

The search strategy used a range of keyword combinations including Lean, product, case study, engineering, Toyota, NPI, development, introduction and aerospace. Wildcard keywords such as coordin* were also used, this particular keyword being intended to capture papers discussing how organisations coordinate resources and undertake cross-functional activities. Thirteen search strings featuring different combinations of key words were used. There are several interpretations of the term 'Lean' and the one that was used here is that chosen by Hines et al (2004). This means that papers dealing with just-in-time, waste reduction or value adding have all been included in this review. Furthermore, as alluded to above, 'white collar' activities or functions that have been considered are those that may have some association with PD such as design, research and development, marketing, sales, production engineering and supply chain management.

The lists of hits for each search string were firstly edited to remove any duplicate records that appeared. The titles were then checked to ensure relevance to the review. Abstracts of all other articles and papers were then reviewed before selecting publications for a full review. During this exercise no restriction was placed on the form of publication so, for example, a series of books with 'Lean', 'product development' and 'new product introduction' in the title were acquired and considered for further review. Similarly, Internet searches using title/author/keyword combinations also proved useful.

3.3 Results and analysis

The search strategy initially identified many relevant publications. Table 1 shows the number of journal articles and conference papers associated with each search string used. In most cases the number of journal articles exceeded that of conference papers. This might be explained by the databases indexing the journals more comprehensively. Many of the 550 publications that were retrieved against the search string 'Lean+product+development' were also retrieved against the other search strings such as 'Lean+product+design' (370 hits) and 'Lean+product+engineering' (845 hits). The large hits score for this last combination reflected the abundance of publications on the operational aspects of Lean manufacturing as well as papers dealing with product engineering for Lean manufacturing. Perhaps surprisingly the search string 'Lean+npi+aerospace' found just 3 publications. Search strings combining 'Toyota' or 'case study' with 'Lean+design' or 'Lean+development' resulted in results more in line with expectations and gave 139 in total.

Following a review of the publications that were retrieved, it was established that at the time of the search there were 24 articles available that are suitable for review as part of this research and that all were published within the chosen timeframe of 1999-2005. These are shown in tables 2 and 3 by author, title and source, in chronological order. Our analysis was then conducted on these particular articles.

Having identified the literature, the first pass of the review process involved briefly summarising each publication against the initial research questions. This enabled a better understanding of the topics covered by these papers and some understanding of the emergent themes. Each of the 24 publications was then read in detail by the researchers and mind mapping techniques were used to capture and represent the consistent messages. These were then distilled into the key findings (topics on which the views of the authors converged) and issues (topics on which authors had differing views). Finally, the results were presented to practitioners to test the readers' interpretations of publications and check that the terminology was precise. On the basis of this analysis, the following key findings were developed.

4. Generation of key findings and issues

The literature review process allowed six key findings and three principal issues to be established. This section presents each in turn.

4.1 The definition of Lean is drifting

In the 1980s Lean was associated with a reduction in waste in the factory, then on quality, cost and delivery during the 1990s before the focus shifted to customer value after 2000 (Hines et al, 2004). Today, the emphasis 'value' and how it can be maximised, is growing in popularity. The shift from waste elimination to value enhancement is exemplified by Browning (2000) who argued that during the PD process maximising value can be achieved by doing more not less. Haque (2004) also argued that engineers need to move from a production focus in which the primary aim is waste reduction to one of identifying and enhancing value. Activities that create useful additional information and/or reduce risk are examples of this. The consequence of this drift is that there is a danger for both researchers and practitioners, of misinterpreting the ideas that are being put forward during any discussion about Lean. It is also important to distinguish between the philosophy, principles, techniques, and values associated with Lean. Again, conversations are frequently held at varying levels, and this leads to our first finding.

> *Finding 1: The definition of Lean is drifting. Whilst earlier papers saw a Lean as a philosophy for waste reduction the emerging view is now one of value creation.*

4.2 Lean is applicable to PD processes

There is a wide variety of examples where Lean has been applied in this context with publications in such fields as software (eg: Middleton, 2001 and Poppendieck, 2005); construction (eg: Javier, 2002) and aerospace (eg: Haque, 2004 and McManus, 2005).

In software the consideration of the waste principle (Poppendieck, 2005) addresses the shortening of long information feedback loops, the existence of which is cited as the reason why over 50% of all newly developed software is seldom, if ever, reused. The result of shortening feedback loops creates flow, increases speed and quality and hence reduces cost and adds value. Middleton (2001), whilst showing how the concepts of Lean manufacturing could be successfully transferred to software development, noted that the major implementation issue was the requirement for deep changes in the way organisations are managed. In his case work Middleton documented an account of the full adoption of Lean by a software development company and concluded that the extensive Lean manufacturing literature is a valuable source of new ideas for software engineering.

Javier (2002) describes the application of the Lean principle of waste elimination in the design process of the construction industry. The design process is conceptualised as a flow of information, which lends itself to waste reduction through minimising the amount of time before information is used. Value generation arises from capturing the customer's requirements and transmitting these accurately in the overall design process.

Haque (2003) reported that the application of Lean to engineering processes in the UK aerospace industry has been lacking, although case studies indicated that the application of Lean to PD was feasible and capable of delivering benefits for large and small companies. In his later work he noted the analogy between the roles of information in the PD value stream and material in manufacturing. This explains his recommendation that engineers focus on the identification and enhancement of value. Similarly McManus (2005) reported that in the US aerospace industry the application of Lean design techniques was underway, but that techniques were not well established, and many practitioners were feeling their way forward.

> *Finding 2: It is clear that Lean can be applied (although the extent is yet to be confirmed) to product design, engineering and development in the aerospace and other sectors.*

4.3 The concept of value in PD needs careful consideration.

Lean is about creating more value for customers by eliminating activities that are considered wasteful. The first principle of Lean is to 'specify value' (Womack & Jones, 1996). They specified value as:

"A capability provided to a customer at the right time at an appropriate price as defined in each case by the customer"

However, when applying these principles to PD it is recognised that waste is much more difficult to identify than in a manufacturing environment. In manufacturing, excess inventory or work-in-progress (WIP), which is considered a form of waste, is physically and financially visible. However, in PD the WIP inventory is generally in the form of information, which is not easily visible and is not easily assigned a financial value.

As a result of work carried out as part of the US Lean Aerospace Initiative, Chase (2000) argued that the usual definitions of value did not provide the necessary precision when applied to identifying the root causes of the waste that is present in most PD processes. He suggests that PD processes can be mapped with two types of waste being labelled as either value-adding, necessary waste (type1 Muda) or waste (type 2 Muda). Any process generating type 1 Muda should be made more efficient to minimise this type of necessary waste without eliminating it. There is a consensus (McManus, 2005; Browning, 2000; Haque, 2004) that value is added in PD when useful information is produced. The value of this information can be to increase certainty or reduce risk. Value in the PD process can be created by adding as well as taking away activities.

Browning (2000) considers equations from several authors defining value as essentially a ratio of benefits to costs. Whilst informative, these equations provided no information about the balance of product attributes preferred by the market or customer. He concludes that,

"all we really know is: Product Value = f(Product Performance, Product Affordability, Product Availability)"

Clearly, the PD process can affect all these variables in a positive or negative way through information generation, process efficiencies and timescales.

Finding 3: Value in the PD process needs to be precisely defined as it is not necessarily the same as value in production operations.

4.4 Adoption of a set-based approach is favoured

Set-based concurrent engineering (or set-based design), as practiced by Toyota, is suggested in the literature (see Kennedy, 2004 and Liker, 2004) as the preferred approach to Lean PD. Set-based design imposes agreed constraints across different functions to ensure that a final sub-system solution, chosen from a set of alternatives from a particular function (such as body, power train, engine management etc), will work with convergent solutions from all other functions. During the design process as each alternative is evaluated, trade-offs are made, weaker solutions are eliminated and new ones are created, often by combining components in new ways. Redundancy is built into the system, radically reducing risk. Instead of being designed from the top down the actual system configuration "evolves" from creative combinations of multiple solution sets.

There is a consensus that this approach is superior to the alternative point-based design process which fails to effectively reuse information/designs and is prone to significant 'rework' costs. McManus (2005) suggests that this is a result of a failure of traditional point-based design to keep the design space open as long as possible. The deferred commitment of set-based design is a strategy for avoiding premature decisions and generating greater value in design (Ballard 2001). In all design processes, alternatives are generated, evaluated and selected. Kennedy (2004) points out that in the Toyota approach of set-based design, all of the knowledge (including knowledge of what did not work) is captured and may be reused in future projects. One hypothesis regarding Toyota's superior performance is that the practice of carrying alternatives forward reduces negative iteration and therefore reduces waste (Ballard 2001). Oppenheim (2004) notes that the Toyota approach requires team training and the dynamic allocation of resources.

Finding 4: The Toyota approach of applying set-based concurrent engineering with parallel evaluation of multiple sub-system alternatives and minimal design constrains provides an effective base for Lean design.

4.5 Strong leadership from the Chief Engineer is critical

There is again consensus in the literature that the key to a successful PD process is strong leadership of an expert Chief Engineer (CE), with total project responsibility, who is supported by experienced function engineers (Haque, 2004; Oppenheim, 2004; Kennedy, 2004). Success does not require the CE to have control over all the engineering resources, but rather that the CE is driven by targets and deadlines, and always willing to step back and reflect on the range of design options available. The allocation of a project manager to administer the programme on behalf of the CE is common practice. Liker (2004) observes that the successful CE is sometimes referred to as a "heavy weight project manager" who has proven engineering excellence, leadership skills to control the programme, and who acts as the critical link between engineering and customer satisfaction.

Finding 5: Adoption of Lean requires strong leadership of a Chief Engineer with responsibility for the total project.

4.6 A Lean culture has the overal greatest impact

The pressure to remain competitive by providing end customer value in delivering the right product, at the right time and at an acceptable price has extended from the mass producers of the automotive and electronics industries, to sectors such as aerospace, which is more characterised by highly differentiated, low volume production. However, irrespective of context, the underlying key to maximising the success of Lean has been the adoption of an organisation-wide culture across all areas in the business.

The book 'Lean Enterprise Value' from MIT's Lean Aerospace Initiative (LAI, 2002) supports the view that the entire enterprise must undergo a Lean transformation for the impact of Lean to be significant. Following the successful integration of Lean principles in manufacturing, McNeel (2004) reported on the successful application of these principles to increase the speed of product design. This required focus across the organisation on programme planning, risk management and problem resolution. Lean PD requires systems engineering to be applied not only to products but also to processes. Design and development engineering and the core support functions need to focus on identifying and enhancing value.

Finding 6: A truly successful application of Lean requires organisation wide changes in systems practices and behaviour.

4.7 Approaches to knowledge/information management are an unresolved issue.

The literature identifies the generation, use and re-use of knowledge/information as key to a successful adoption of Lean in PD (Liker, 2004). Reinertsen (2005) captures this with the phrase "The work product of PD is information". Standardised concurrent engineering techniques have been shown to be highly effective in sharing and reusing knowledge/information at the detail design phase Kennedy (2004). Likewise, the sharing of design (and manufacturing knowledge) across the product introduction process is viewed as a knowledge management problem (Mountney et al, 2005). The challenge is in ensuring that the information is structured in such a way as to make it communicable between systems. Haque and James-Moore (2002) suggest that systems for controlling documents, central databases, knowledge-based systems, project management systems, CAD/CAM/CAE/PDM systems and web-based data sharing and communication tools can all be used to facilitate Lean. However, the form that such systems should take is not yet clear.

Issue 1: The standardisation of knowledge / information management processes that support the adoption of Lean in PD are yet to be defined.

4.8 The elements of the PD process that truly create value remain an unresolved issue.

Producing the right information in the right place and at the right time creates value in the PD process (Browning, 2000) and the timely use of such information minimises waste during the process. Poppendieck (2005) cites the existence of long information feedback loops in software development as a source of waste. The development of a design creates economic value by generating information. Likewise, Ballard (2001) considers iteration in the design process to be essential for the creation of value in PD and iteration that can be eliminated without value loss is waste. This of course refers to positive iterations rather than those which are undertaken as a result of the provision of incorrect or incomplete information.

A decrease in risk is regarded as an increase in value (Chase, 2000) since this will increase the likelihood of delivering the required product specification to the required schedule. Reinersten (2005) comments that "In PD rational risk-taking is a major mechanism for adding value, which is not the case in manufacturing where risk taking adds variability and reduces economic process performance". It is crucial therefore that there is a workflow balance in PD to facilitate the flow of value and ensure that activities and processes produce and consume 'deliverables' at the right time.

Issue 2: The key areas of value creation in the design process remain unresolved.

4.9 The extent to which workflow should be re-engineered is an unresolved issue

Oppenheim (2004) proposes a Lean product development framework (LPDF) which incorporates the concepts of both the moving line (continuous flow of work pulsed by Takt times) and Lean production (pulled deliverables, focus on delivering maximum value with minimum waste). This approach requires the parsing of the value stream into a large number of Takt periods of equal and short duration, but not necessarily requiring equal effort or team composition. The necessary resources are dynamically allocated as required.

Studies of the utilisation of product development capacity, involving 400 organisations over 11 years, show an utilisation rate of over 95% (Reinertsen, 2005). When combined with variability in both project duration and work content, this creates the perfect conditions for long queues. These organisations therefore create a form of waste equivalent to that associated with excess manufacturing inventory. Unlike their manufacturing counterparts however, product developers appear to do little to measure or manage these queues. Lean methods offer a proven and sophisticated approach for dealing with the high inherent variability of PD, however the extent to which such re-engineering is feasible is difficult to judge.

Issue 3: The extent to which the entire product development work flow needs to be re-engineered, in the adoption of Lean, needs to be better understood.

5. Conclusions

The findings (table 4) confirm the view that Lean can be beneficially applied away from the factory; that an understanding and definition of value is key to success; that a set-based (or Toyota methodology) approach to design is favoured together with the strong leadership of a Chief Engineer; and that the successful implementation of Lean requires organisation-wide changes to systems, practices and behaviour. The principal issues concern the approach to defining the processes of Product Development (PD) that create value; the role of standardisation in information management; and whether the entire product development workflow needs to be re-thought. By establishing these findings and issues, this paper provides a state-of-the-art review of work on this topic, and so provides a theoretical platform on which to base more in-depth case studies.

In addition, and at a more general level, it is apparent from this review that Lean product development is an emerging topic. When conducting the initial searches many thousands of papers were found that are associated with the topic of Lean. Even when restricting the scope of the study to consider only Lean operations a very considerable literature base was found. However, after very careful filtering only 24 authoritative publications were found that are associated with Lean PD. The conclusion of this review supports that of McManus (2005) that the techniques of Lean PD are not well established and many practitioners are essentially 'feeling their way'. Quite clearly many opportunities exist.

As for future work, the key findings and issues arising from the evidence gained in the literature need to be tested, in particular confirmation of the widely acclaimed 'Toyota approach'. Therefore, the intention of the authors is firstly to identify a number of organisations that could reasonably be expected to exhibit leadership in the adoption of Lean PD and then to undertake structured and in-depth cases studies of the PD processes in these organisations.

Table 1: Literature Keyword Search Results

	Key Words Searched	Number of Article Hits	
		Conference paper	Journal paper
S1	Lean+product+development	140	410
S2	Lean+product+introduction	10	30
S3	Lean+product+design	100	270
S4	coordin*+Lean+design	10	14
S5	Lean+npi+development	1	3
S6	Lean+npi+product	1	3
S7	Lean+npi+case study	0	1
S8	Lean+npi+aerospace	1	2
S9	Lean+product+engineering	245	600
S10	llean+design+toyota	4	16
S11	Lean+design+case study	45	45
S12	Lean+development+toyota	7	30

Table 2: Key Research Papers Identified

Author	Title	Source
Karlsson, 1996	The Difficult Path to Lean Product Development	J.Prod.Innovation Management
Blackler, 1999	Managing Experts and Competing through Innovation: An Activity Theoretical Analysis	Organisation Articles – Sage
Browning, 2000	Value –Based Product development : Refocusing Lean	Proc IEEE 2000 Engineering Management Society
Chase, 2000	Measuring value in product development	Lean aerospace initiative MIT
Ballard, 2001	Positive vs. Negative Iteration in design	Lean Construction Institute

Middleton, 2001	Lean software development: two case studies	Software & quality Journal
Freire, 2002	Achieving Lean Design Process	J. Construction Engineering & management
Haque, 2002	Characteristics of Lean product development	I.J. Automotive Technology and Management.
Morgan, 2002	Lean principles and product development	Standardization News
Haque, 2003	Lean engineering in the aerospace industry	Proc . I Mech. Engineers
Haque, 2004	Applying Lean thinking to new product introduction	J Engineering Design
Haque, 2004	Measures of performance for Lean product introduction in the aerospace industry	Proc . I Mech. Engineers
Oppenheim, 2004	Lean Flow Product Development	Systems engineering
Kennedy, 2004	The Toyota product development system	Machine Design
Reinertsen, 2005	Achieving Lean product development	Engineering Technology
Reinertsen, 2005	Let it flow	Industrial Engineer
Rich, 2005	Thinking Lean	Manufacturing Engineering

Table 3: Key Conference Papers, Theses and Books Identified

Author	Title	Source
Mc Manus, 2005	Lean engineering: Doing the Right Thing Right	Int. Conf. Innovation & Integration in Aerospace Sciences
Middleton, 2005	Lean software management case study: Timberline inc.	Extreme Prog.& Agile Processes in S/W Eng. I. Conf. XP
Poppendieck, 2005	Introduction to Lean software development practical approaches for applying Lean principles to software	Extreme Prog.& Agile Processes in S/W Eng. I. Conf. XP
Mountney, 2005	Requirements of a hybrid social-technical knowledge system to support the use of manufacturing knowledge during preliminary design	Cranfield University
Reinersten, 2005	The Impact of Lean Thinking'	Knowledge Round Table Interview
Cleveland, 2005	Toyota's Other System – This One for Product Development	http//www.autofmg.com/columns/0206/ insight.html
<u>Books</u>		
Fiore, 2004	Lean Strategies for Product Development	ASQ Quality Press
Kennedy, 2004	Product development for the Lean Enterprise	The Oaklea Press
Liker, 2004	The Toyota Way	McGraw-Hill

Table 4: Summary of key findings and issues

Topic	Key Finding / Issue
Definition of Lean	The definition of Lean is drifting. Whilst earlier papers saw a Lean as a philosophy for waste reduction the emerging view is now one of value creation.
Applicability of Lean	It is clear that Lean can be applied (although the extent is yet to be confirmed) to product design, engineering and development in the aerospace and other sectors.
Value in Lean	Value in the PD process needs to be precisely defined as it is not necessarily the same as value in production operations.
The Approach to Lean	The Toyota approach of applying set-based concurrent engineering with parallel evaluation of multiple sub-system alternatives and minimal design constrains provides an effective base for Lean design.
Lean Programme Management	Adoption of Lean requires strong leadership of a Chief Engineer with responsibility for the total project.
Lean Culture	A truly successful application of Lean requires organisation wide changes in systems practices and behaviour.
Management of Knowledge and Information	The standardisation of knowledge / information management processes that support the adoption of Lean in PD are yet to be defined.
Value creation	The key areas of value creation in the design process remain unresolved.
Work Flow	The extent to which the entire product development work flow needs to be re-engineered, in the adoption of Lean, needs to be better understood.

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