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A review of designing machine tool for leanness

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Abstract. As an ideology, Leanness is not a new concept but still researchers strive for developing new methods to reduce almost all kinds of identified wastages at almost every stage and in every activity — right from design till delivery of final product to the end-customer. Newly developed manufacturing ideologies, paradigms and systems are always critically examined from the point of view of leanness. In other words, leanness is becoming an important evaluation tool to compare the recently developed/pioneered approaches. There has been a gradual evolution of the leanness over the years from the shop floor level of a manufacturing (automobile) organization to almost every operational and management aspect now. The Leanness has undergone and still is undergoing a process of continuous and never-ending evolution due to its inherently built dynamic concept of continuous improvement. Although in the literature a lot of work has been reported to the application of lean tools, principles, theories and methodologies to production systems, but a very few is evident in the area of Lean design process of a product and machine tool. For this reason an attempt is being made here to focus a significant proportion of this paper on evolutionary aspect of leanness from manufacturing to design stage. Also, this paper reviews the concepts and practices being followed till date by the industrialists, researchers and academicians in applying lean tools and techniques in the design of product and machine tools along with the methods to measure the lean improvements in the systems.

Keywords. Leanness; waste elimination; lean machine tool; lean assessment; dynamic continuous improvement.

1. Introduction

The principles of lean manufacturing were introduced by the Toyota Production System (TPS) in 1950 in Japan. Since then a considerable amount of work has been reported in the area of

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the Lean Manufacturing (LM), but the application of leanness to other stages of Product Life-Cycle and in design of machine tools has not been explored extensively. In fact, the work in the direction of Lean Manufacturing has almost saturated now and a very few literature exists that advocates Lean application in design and development process of a new product and a machine tool. Practical industrial applications of lean design process is almost non-existent. What is missing in the literature is the sequential/hierarchical approach to the design process and the problems addressed seem to be too general to be focused upon. The dynamism (continuous improvement) aspect of leanness is becoming the compelling force for the researchers to explore it (leanness) further in the design of products and machine tools.

Houshmand & Jamshidnezhad (2006) proposed a hierarchical structure to model the design process of a lean production system utilizing axiomatic design. The approach consisted of relationships between functional requirements, design parameters and process variables to reduce much of waste associated with trial-and-error design process. It was asserted that the general lean production system design (LPSD) model developed here could be applied to any variety of production system but it lacked practical industrial applicability and needed further validation. Moreover, the lean design aspect of product/machine tool was not at all addressed.

A number of Lean Assessment systems are available nowadays to evaluate the level of implementation of leanness in an organization but no such assessment system exists for lean design process which itself is in infant stage. There is a need for the development of similar assessment systems in the field of Design Process so that the organizations may become familiar with the areas they need to improve upon to make their design process leaner and to produce better end-products with lean machine tools in lean time with less cost.

2. The lean conceptual ideology

Leanness is the search for perfection through the elimination of wastes and the initiation of practices that contribute to the reduction in cost while improving performance of products including the machine tools. Monden (1998) revealed that although the lean philosophy was born in UK during second world war, the real work was done at the Toyota Motor Company in Japan in the 1950s and was later coined as 'Toyota Production System (TPS)'. Lean Manufacturing is now renowned for its focus on reduction of the original Toyota eight types of wastes in order to improve overall customer value.

These identified wastes in TPS are:

(i) Overproduction (production ahead of demand)
(ii) Transportation (moving products not actually required to perform processing)
(iii) Waiting (waiting for the next production step)
(iv) Inventory (all components, work-in-progress and finished product not being processed)
(v) Motion (walking or moving of people or equipment more than what is required to perform processing)
(vi) Over processing (due to poor tool or poor product design creating activity)
(vii) Defects (the effort involved in inspecting for and fixing defects)
(viii) Unused creativity.

Thus, in a manufacturing environment, the waste has been defined as any redundant application of resources that does not add value to the product i.e., the activities for which the customer is not willing to pay. These manufacturing wastes include over-production, work in progress

(WIP) inventory, finished goods inventory, waiting (idle) time, inappropriate processing, unnecessary motion, transportation, defects, etc. Scrap, unneeded items, old/broken tools, and obsolete jigs and fixtures have also been considered as wastes. TPS is now a well-established philosophy in the manufacturing world that really endeavours for integrating and shortening the timeline between the supplier and the customer by eliminating hidden wastes (Sahoo *et al* 2008).

Lean as a philosophy was initiated by the coinage of the term 'Lean Manufacturing' by Womack *et al* (1990) in the book '*The machine that changed the world*'. Every industrialized country has now fully recognized the importance and potential benefits of practically implementing the theory, principle and methodologies of lean ideology (De Meyer & Wittenberg-Cox 1992). Lean manufacturing (LM) is lean because it uses less of everything—compared with mass production—half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time. Papadopoulou & Ozbayrak (2005) highlighted the inherent dynamism in leanness that it is still undergoing a long evolutionary process through various stages of its existence. The study critically questioned the limited applicability of leanness in high variety low volume (HVLV) production systems. It delineated a logical need to further explore the lean enterprise, its potential future forms, dynamics and its association with different paradigms.

The implementation of lean principles in any organization begins by identification of the value stream, i.e., all those activities (value-adding or non-value-adding), required to manufacture a product or to provide a specific service to a customer. The numerous activities performed in any organization can be categorized into the following three types (Monden 1998):

(i) Value adding Activities (VAA)—which include all of the activities that the customer acknowledges as valuable i.e., for which he is ready to pay.
(ii) Non Value Adding Activities (NVAA–Type II Muda or Obvious Wastes)—These include all the activities that the customer considers as non-valuable, either in a manufacturing system or in the service sector. These are pure wastes and involve unnecessary actions that should be eliminated completely. Some examples of these are waiting time, double handling, defects, etc.
(iii) Necessary but Non Value Adding Activities (NNVAA - Type I Muda)—These include the activities that are necessary under the current operating conditions but are considered as non-valuable by the end user i.e., the customer. These types of operations are difficult to remove in the short run and hence should be targeted in the long run by making major changes in the operating system. These include activities like walking long distances to pick up goods and unpacking vendor boxes.

Out of these, the non-value adding activities are a waste that need to be totally removed, if possible, under the present work conditions. The principles of 'Lean Thinking' aim at achieving a systematic approach for identifying and eliminating these wastes through continuous improvement.

3. Lean manufacturing, tools and assessment

3.1 *Lean manufacturing (LM)*

LM is a manufacturing paradigm which continuously aims at not only reducing but finally eliminating all forms of non-value adding work/activity in any production process by achieving continuous one-piece-flow. The continuous flow concept of LM ensures the shortest lead time, with the best quality, the lowest cost and the highest safety and morale of the workers. It provides a set of tools and an underlying philosophy which aids in making a production system more efficient and effective. Shah & Ward (2007) proposed a new definition to capture many facets of lean production as – '*Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability*'. According to Detty & Yingling (2000) Lean manufacturing is a philosophy for structuring, operating, controlling, managing, and continuously improving industrial production systems. Holweg (2007) investigated the evolution of the research at the MIT International Motor Vehicle Program (IMVP) that led to the conception of the term 'lean production'. Liker (1998) targeted the goal of lean manufacturing towards minimization of waste in terms of non-value-added activities, such as waiting time, motion time, set-up time, and WIP inventory, etc.

Lean manufacturing is viewed as a five-step process: defining customer value, defining the value stream, making it flow, pulling from the customer back, and striving for excellence. Arguably the toughest and the least understood among these is the fifth step i.e., the effort to continuously improve (striving for excellence) by eliminating all the root causes of the problems. This requires a learning organization which values its people such that they not only accept but also start to embrace changes. People at all levels need to be educated and empowered to unhide wastes and remove them with help of the others, a process popularly known as Kaizen or continuous improvement. Bhuiyan & Baghel (2005) conducted studies on the history and evolution of Continuous Improvement (CI), its impact on the organizations and identified the tools and techniques needed to achieve the ongoing cycle of improvement. Ahlstrom (1998) explored that the manufacturing organisations needed to devote effort and resources to implementing lean production principles leading to continuous improvement both in parallel and sequentially.

Detty & Yingling (2000) quantified the benefits of conversion into lean manufacturing with discrete event simulation. The prescribed simulation methodology provided a considerable savings in the shop floor resources while improving time-based performance statistics. Shah & Ward (2003) conducted studies on the effects of three factors—plant size, plant age, and unionization status, on the feasibility of implementing the key tools of lean production systems. They substantiated a strong support for the influence of plant size on lean implementation and concluded that lean implementation itself contributes significantly to the operating performance of a plant.

The success rate of successful industrial lean implantation has been evidenced to be low as suggested by Bhasin & Burcher (2006). Only 10% or less companies are successful in implementing lean manufacturing practices. The failure organisations view lean as a process/strategy and not as a long term philosophical journey, which require at least 3 to 5 years to show any results. They lack direction, planning and adequate project sequencing, a continuous improvement viewpoint; necessity to make several cultural changes to sponsor lean principles through-out the value chain.

Domingo *et al* (2007) undertook an industrial case study of assembly line improvement by means of lean metrics attempting to reduce the dock-to-dock time and to increase the lean rate. The applied lean principles helped the organization to attain lowest cycle time and to reduce waste in terms of unnecessary inventories, excessive transportation and idle times, without changing the production philosophy or layout. Braiden & Morrison (1996) proposed some of the basic lean tools to increase the production capacity of Automated Monorail System as the motor compartment production line was a complex system involving many subassemblies.

Shahram & Berro (2006) applied the principles of lean manufacturing and constrained management along with matrices as analytical tools to map the sequence of robotics movements to identify interference and desired path for welding line. Constrained management was used to identify bottlenecks in the plant that limits the throughput and lean manufacturing helped to identify waste (muda) in the constrained production areas. By more effective designing and scheduling the movement of robots: removing non-essential welds reduced cycle time from 62 seconds to 60 seconds. Muda of unclamped movements was identified and it helped increase the speed from 70% to 90%, thereby decreased the cycle time by 65 seconds to 62 seconds. Elimination, of the muda of robot–robot interference wait time took the process from 60 seconds to 55 seconds.

Logendran *et al* (2006) advocated the benefits of lean manufacturing system by minimizing the make-span of a two-machine, sequence-dependent group-scheduling problem in hardware manufacturing. Brandon & Morrison (1996) studied the development of a production system for automotive component applications consisting of benchmarked global best practices The production system utilized the lean concepts of project management, process flow, layout, material flow, ergonomics, workplace organization, people-focused practices, and supporting software development as an integrated whole system. This competitive manufacturing system increased the productivity by 25% in a short period of time.

A plethora of literature is available that advocates the several attempts of lean implementation practices in industries around the world notable among them being USA, UK, Japan, China, Australia. Motwani (2003) studied the factors that facilitated and inhibited the successful lean manufacturing implementation experience in a medium-sized automotive company in USA. After three years of implementation, it was observed that production batch size shrunk from 30 to 16 days, set up time reduced by half, prototype development time reduced from 10 months to 10 weeks. Dennis & Comm (2000) developed an eight-step strategy to transfer the best of lean practices of development and implementation from Japanese and US automobile industry into aerospace, defense launch vehicle, spacecraft, and space operations industries. It is emphasized that the lessons learned could be employed to many other industries. These steps included: building the lean consortium; targeting potential stakeholders; deciding on the research agenda; testing the research approach; benchmarking; analysing and assessing the findings; implementing the concepts; and establishing controls to see if desirable results are achieved. Katayama & Bennett (1996) studied the impact of lean production in Japanese industrial and economic environment and advocated that Lean production is a competitive and effective method of manufacturing but it lacks the ability to accommodate the variations or reductions in demand for finished products. Only small changes in demand often takes production to below the break-even point. They suggested that the Adaptable Production enable the organization to operate with lower fixed costs and thereby benefit from a higher variable cost element. The additional features of adaptable production help to improve its ability to produce a mix of products and number of varieties efficiently while still remaining competitive as well as strategically viable. Sohal & Egglestone (1994) identified the need for the Australia's manufacturing industry to adopt lean production principles with a focus on customer-oriented business along with a flexible production structure. The direction of change must come from the top of the organization and filter down very quickly to all levels. Above all, there must be a commitment to change rather than carrying out change for change's sake. Emiliani (2006) provided a historical account of spread of Lean management in USA through connecticut business. The main focus was on 'continuous improvement' especially the operational methods which helped to achieve improvements in productivity and quality, reductions in defects and lead-time and savings in cost. However, it was emphasized that 'respect for people' concept was not understood by most management practitioners, thus hindering efforts to correctly practice Lean management and improve business performance. Herron & Hicks (2008) studied the productivity improvement impact of innovation transfer consisting of selected lean manufacturing tools and techniques into the companies in the North East of England and the initial results obtained from 15 companies showed that the savings are eight times greater than total costs. The process is still continuing but the key determinants of success are the commitment of management and the ability of the change agents to transfer the lean knowledge. Barker (1994) emphasized in particular context to UK manufacturing organizations in electrical switchgear industry that by focusing upon value adding activity, the non-value adding waste, complexity and cost can be reduced progressively to achieve world class competitiveness. But for this, a time based value adding framework to direct development and continuous improvement need to be described. The total conversion chain from raw materials purchase to final goods assembly is examined using this approach without using MRP environment and by using a Kanbun type pull system.

Crute *et al* (2003) examined the Lean implementation to aerospace sector to contradict the general belief that Lean manufacturing is an 'automotive idea' and is difficult to transfer to other sectors. It was argued that difficulties in Lean implementation have more to do with individual plant and management context than with sector-specific factors. Hunt & Poltrock (1999) documented the concepts, goals, planning methodology, resulting design, and subsequent performance of the pilot space. The project design process was influenced by the workflow principles used in Boeing's airplane design and manufacturing processes. These processes were drawn heavily from the 'Lean Enterprise Model' developed by the Massachusetts Institute of Technology in conjunction with a consortium of private enterprises. Acaccia *et al* (1995) developed a software simulation based intelligent manufacturing system for a pilot CIM facility that could be used for simulating the evolution of the material processes in parallel with emulating the control and management logic of the governing product and production processes which could help in the attainment of a lean engineering organization. Sahoo *et al* (2008) successfully mapped Taguchi's method of parameter design in lean environment of a forging shop floor in India with the aim of testing several lean strategies to eliminate waste (non-value added activities) through systematic application of value stream mapping (VSM). The present and future states of value stream maps were constructed to improve the production process by identifying waste and its sources. Taguchi's method of DOE (design of experiments) was used to minimize the forging defects produced due to imperfect operating conditions. A considerable reduction in set-up time, work in progress (WIP) inventory level and defect level for the radial forging operation was noticed in the research.

Even the **economical recovery of defective products** provides leanness to an organization. Rubio & Corominas (2008) proposed a decision making model to introduce a reverse-logistics (remanufacturing) system for used products in a company that uses a JIT production system so that a manufacturing process could adjust its capacity to demand in order to avoid inventory generation and excess capacity. Three decision variables identified for formulating optimal policies were manufacturing and remanufacturing capacities, return rates, and use rates for end-of life products. The model examined the effects of modifying the capacity of the system by establishing a process of economic recovery of used products. It also analysed the transfer of capacity between manufacturing and remanufacturing lines.

Apart from abundant case studies available in manufacturing shop floor, the literature shows that the lean concepts have been and still are being applied to **other operational aspects** also. Emiliani (2001) suggested the investment analysts to change to 'muda analyst', with a focus on elimination of waste in business processes and between internal and external stakeholders to improve the financial performance of the company. Lean production promotes greater clarity and improved responsiveness to changing market conditions and investment analysts should analyse the non-financial measures first because that is where the money really is. Non-financial metrics such as time, distance, space, days of inventory, percent on-time delivery, defects, productivity, customer satisfaction, etc. are what drive financial performance and promote the integration of stakeholders to achieve sustainable business results. The work of financial analysis becomes easier when waste is eliminated. Emiliani (2004) described the application of lean principles and practices to the design and delivery of a graduate business school course which resulted in a higher level of student satisfaction through clearer expectations, less ambiguity regarding assignments, standard formats for assignments, smoothing individual and team assignments over the semester, and better management of students' time especially both in and outside class. Andrew Crowley (1998) concluded that computers can speed up a production process but it is not a panacea for poor productivity and poor profitability. In particular reference to construction industry, it was suggested that if lean production philosophy is correctly applied, it will allow integration of internal processes and enable concurrent re-engineering to produce high quality buildings at reduced cost.

Fostered by a rapid spread into many other industry sectors beyond the automotive industry, there has been a significant development and 'localisation' of the lean concept. Still the lean approach is often criticised on many accounts such as the **lack of human integration** or its limited applicability outside high-volume repetitive manufacturing environments (Hines *et al* 2004). Spithoven (2001) argued that a shift from traditional mass production to Lean production made the work harder, demanding and stressful for the employees leading to disabilities and mental disorders. Kinnie *et al* (1998) concluded that Lean organisations often become mean as they achieve higher productivity with fewer employees. Organisations seldom gain the benefits of increased efficiency associated with lean production, but reap all the drawbacks of meanness. It is strongly advocated that the real benefits of lean practices can be achieved only when human resource concerns are paid full attention and consideration.

One of the **limitations** of lean enterprise has been the lack of creativity in subsequent years after its implementation and obtaining benefits in earlier years as concluded by Lewis (2000). He argued that lean production can provide competitive advantage if the firm is able to appropriate the value generated by productivity savings. Secondly, as the firms become more 'lean' they inevitably see a narrowing of innovative activity and a curtailment in the achievement of long-term flexibility. Browning & Heath (2009) delineated through the case study of the F-22 program that lean implementation is not simple and it may provide mixed results in various organizations. It was concluded that timing, scale, and extent of lean implementation matters most and that the reduction of waste is better construed as the provision of value, and that this value is an emergent property of a process—implying that lean is not the guaranteed result of the elimination of tasks.

3.2 *Lean tools and techniques (LTT)*

Most of the lean manufacturing activities are concentrated on the shop floor only. Many lean concepts and tools have been developed to eliminate different kinds of wastages in order to optimize various activities of production. Usually Lean is considered to be a set of 'tools' that assist in the identification and steady elimination of waste (Muda). As waste gets eliminated, the quality of the product improves while production time and cost is reduced. In manufacturing, many such tools have already been identified and are being applied. Some of these 'tools' consist of Value-Stream Mapping (VSM), Kanban (pull systems), Poka–Yoke (error-proofing) 5S (sort, set in order, shine, standardize, sustain), Heijunka (production smoothing), Kaizen (continuous improvement), SMED (single-minute exchange of die), TQM (total quality management), JIT (just-in-time), TPM (total productive maintenance).

Besides these tools 6σ (six sigma) has also been associated with Lean Manufacturing with the name Lean Six Sigma whereby lean manufacturing refers to speed and six sigma refers to product quality. The two are related, but distinct. Six sigma focuses on the reduction and removal of variation by the application of an extensive set of statistical tools and supporting software, whilst lean thinking focuses on the reduction and removal of waste by process and value analysis (Tony Bendell 2006). Edward & Maleyeff (2005) concluded that the joint implementation of both lean and six sigma programs will result in a Lean Six Sigma (LSS) organization thereby overcoming the limitations when implemented in isolation. The combined strategy would provide a LSS organization the strengths of both lean management and Six Sigma. Andersson *et al* (2006) argued that TQM, six sigma and lean are similar in origin, methodologies, tools and effects but are different in theory and approach. It was found that TQM and six sigma show many similarities, while the lean concept is slightly different compared to these two. Further, six sigma and lean are excellent road-maps to strengthen the values of TQM within an organization. It was recommended however that the organisations will gain a lot if these three complementary concepts are combined together.

Narasimhan *et al* (2006) figured that the essential aspect of leanness is the efficient use of resources through the minimization of waste. Lean manufacturing focuses on reducing wastes and non-value adding activities of many types. Production is agile if it efficiently changes operating states in response to uncertain and changing demands placed upon it. Production is lean if it is accomplished with minimal waste due to unneeded operations, inefficient operations, or excessive buffering in operations. So it is concluded that while agility presumes leanness, leanness might not presume agility. Prince & Kay (2003) developed a methodology to combine agility and leanness within a cellular manufacturing system by the creation of virtual groups (VGs) identified through enhanced production flow analysis (EPFA). Agarwal *et al* (2006) explored the relationship among lead-time, cost, quality, and service level and the leanness and agility of a case supply chain in fast moving consumer goods business. The ANP (analytic network process) approach was used. Leanness in the supply chain maximized profits through cost reduction while agility maximized profit through providing exactly what the customer requires. The leagile supply chain enabled the upstream part of the chain to be cost-effective and the downstream part to achieve high service levels in a volatile marketplace. Cagliano *et al* (2004) conducted studies on Lean, Agile and traditional strategies in the supply chain separately on European companies in Engineering sector and concluded that both Lean and Agile strategies perform better than any other combination of strategies, and that neither of them is clearly the best. Krishnamurthy & Yauch (2007) applied the concept of leagility (Lean+Agile) to a single corporation with multiple business units which was otherwise being used in supply chains and in single manufacturing facilities. Determining whether to call a manufacturing system leagile depends on where a boundary is placed around the system or sub-units within the system. A leagile model was proposed and it was concluded that the agile and lean portions of the system are both within the corporate boundary but separated by a decoupling point.

The literature is replete with implementation of different combinations of various lean tools suitable to a particular process, system, product, organisation, size, time, etc. Dhafra *et al* (2006) developed a new synergistic lean tool comprising of SPC (statistical process control), PAC (process attribute chart) and DAM (defect analysis matrix) on per hour basis to fast identify the source/presence of a quality defect on a product followed by taking corrective actions. After 10 weeks of study a 9% reduction in defects was noticed. Almannai *et al* (2008) through industrial validation proposed a manufacturing automation decision-making tool based on combined form of two lean techniques i.e., quality function deployment (QFD) and the failure mode and effects analysis (FMEA) to incorporate human, technical and organizational factors in a production system design. Jones *et al* (1999) discussed the application of value stream analysis (VSA)—a tool for exposing waste and root cause analysis (RCA)—a method for pursuing perfection, as lean tools and techniques in service industry environment specially to a communications provider organization. Abdulmalek & Rajgopal (2007) studied the application of lean principles in a large integrated steel plant in process/continuous sector using VSM as main lean tool. Through the development of a simulation model, the reduced production lead-time and lower WIP inventory was reported in the study.

Herron & Braiden (2006) developed a three-step methodology for sustainable productivity improvement of manufacturing companies after identifying and drawing some successful lean tools from an exemplar company Nissan Motor Manufacturing UK Ltd. The Productivity Needs Analysis (PNA) was used to study the current manufacturing condition of the company and to identify the key productivity measures to improve efficiency. In Manufacturing Needs Analysis (MNA), the identified plant processes and problems were associated with the appropriate lean tools and metrics to obtain the numerical ranking as output. Finally, PNA and MNA were combined with a Training Needs Analysis (TNA) to ensure that the efficacious tools are fully embedded within the company. Shah & Ward (2007) identified 48 practices/tools as representing the operational space of lean production which were ultimately distilled into 10 positively and significantly correlated factors of measurement as supplier feedback, JIT delivery by suppliers, supplier development, customer involvement, pull, continuous flow, set-up time reduction, TPM, SPC and employee involvement. It was asserted by the researchers that these 10 underlying constructs could be effectively used to assess the state of lean implementation in firms and to test hypotheses about relationships between lean production and other firm characteristics that affect firm performance. Buyukozkan *et al* (2004) studied the synergistic impact of methods and tools of concurrent engineering and new product development in association with agile manufacturing to enable a flexible, adaptive and responsive manufacturing organization to develop a variety of product at low cost and in a short time period.

3.3 *Lean assessment systems (LAS)*

An important aspect regarding the Lean Manufacturing is the existence of a number of assessment systems. Some of the corporates have now even developed the various assessment systems to evaluate the extent of leanness at the shop floors of manufacturing organizations. Some of the leading organizations providing these assessment systems are ISI Lean Value Assessment (Industrial Solutions Inc.), Assessment (Lean Enterprise Inc.), Stratergos Assessment (Strategos Inc), Lean Self-Assessment Throughput Solutions, Shingo Assessment (www.shingoprize.org), Sai Global Assessment, etc. According to Jaitly *et al* (2008) all these systems followed a similar and logical pattern of asking certain questions of the organization being judged. The questions were grouped under certain parameters which were largely different for different systems. Assessment from Lean Enterprise provided with a different perspective in that it had a format in which the response to a question was to be put under one of 3 categories namely mass manufacturing, beginning lean and world class with 1, 5 or 10 marks awarded correspondingly. ISI system was the most comprehensive of the lot, it even covered the management perspective, but this in turn made it very bulky. Also, following common problems were found in these existing tools (Jaitly *et al* 2008).

- Lack of structure: Even though the questions were clubbed under certain parameters, the significance of the parameters was not clear. Also it did not indicate which manufacturing waste it was addressing.

- Repetition: Many parameters were often repeated leading to redundancy and an incorrect representation of the present state.
- Equal or inappropriate weights given to the parameters: The parameters on the basis of which an organization was judged were often given equal weights. Also, the weights given to a particular parameter did not mirror that parameter's importance.
- More stress on the lean tools: Without much consideration to the role of the people involved.
- Too bulky or complex: In an effort to make the assessment tool as exhaustive as possible, the tool often became too bulky and complex to be of any practical use.

It is evident from the literature that cost and time related pictorial graphs can be effectively used to visualize the benefits provided by using lean techniques. Rivera & Chenb (2007) developed cost time profile (CTP) and cost time investment (CTI) graphs as very useful and effective tools for evaluating the improvements achieved by the implementation of Lean tools and techniques. These tools immediately highlight the economic impact of time improvements, cost reductions and have the ability to assess the expected impact of a change in the production process. However, the literature showed that no such system existed for lean assessment of a design process.

Shahram Taj (2005, 2008) applied an assessment tool to evaluate actual manufacturing practice related to key areas of inventory, team approach, processes, maintenance, layout/handling, suppliers; set-ups, quality, scheduling and control to 65 Chinese manufacturing plants. It was reported that the lean production system design-related questions showed low scores in layout design, volume/mix flexibility, set-up, visual factory, and point-of-use delivery. However, plants earned high scores in materials flow, scheduling/control, on-time delivery of finished goods, and overall defect rate. The competitive Chinese companies are producing and marketing their own brands globally and have even launched manufacturing facilities in Western countries. They are now emerging as powerful rivals to several multinational companies in the global market. Several Chinese companies have created brands that have taken the market share from stronger rivals in Asia, Europe, and the USA. The assessment of 65 manufacturing plants also showed that there is still a significant gap in the achievement of set lean targets.

4. Lean design of product: The innovative need of the hour

Today very little knowledge is available about the application of Lean concepts in design process of a product, though a plethora of literature exists about practical application and implementation of Lean tools and concepts in manufacturing. There is a clear difference between lean manufacturing and the lean design. Only a few people have identified this and worked upon it. Tim Helton (www.techsolve.org) stated that 'Lean-manufacturing concepts have permeated all corners of many a shop floor except within the machining center.' He also reported that the major eight Toyota manufacturing wastes have been identified only on the shop floor and that only one of them i.e., the unused creativity points towards leanness aspect of the design of the product. He suggested that making the design lean, practicing Kaizen event and developing value stream mapping would further help in cutting down the cost of production.

4.1 *The lean design process (LDP)*

The success of a lean organization depends on well-designed parts through an equally optimized design process. The importance of optimized or minimum wastage bearing Design Process within Product Life-Cycle has been highlighted by virtually all businesses that have adopted this contemporary lean approach. It has been established that Lean Manufacturing itself is not enough to keep the competitive edge in the market. Faster time-to-market with competitively priced products that delight the customer is the key. Moreover, lean decisions made during the initial product development can remove many of the critical cost factors in a product, making it impossible to significantly reduce costs later on. It is precisely in this stage only when the voice of the customer is identified and converted into a product. If this is not done in an effective and efficient way, it will lead to increase in the number of iterations before the final product and thus, further cost additions. By applying lean concepts to the Design Process the overall lead time can be definitely reduced and the products can be made according to customer's satisfaction and price expectation.

Although a number of publications exist in this regard, none of them provide a practical knowledge base for the organizations which they can apply to eliminate the wastes and make themselves leaner. Hines *et al* (2005) introduced of Lean in the New Product Development. ETI Group on their website (www.etigroup.com) discussed the importance of lean in design process by cost cutting and time slashing methodology. In the book, *Lean product development* by C Mynott, much emphasis has been laid onto the importance of lean in design process.

4.2 *The stages of lean design process*

The Leanness in design process has been the most under-utilized part so far. There is a need to identify the common tools that can make a Design Process leaner which involves the elimination of wastes or unwanted activities in design (Garg *et al* 2008). But it is essential first to understand the different stages of the Design Process (figure 1) and what tools make the design process leaner.

4.2a *Understanding the customer's needs*: The starting point for any Lean Thinking process is the proper identification of customer needs as advocated by Womack & Jones (1996). Most of the wastes that occur during the Design Process regarding the technical aspects are related to not identifying accurately the customer's needs and requirements. For recognizing the customer's specifications, QFD (Quality Function Deployment) is a very important tool to use which is also called as the 'house of quality'. The House is divided into several rooms. Typically customer requirements, design considerations and design alternatives are arranged in a 3-dimensional matrix to which weighted scores based on market research information can be assigned. Cross functional teams participate in the process that consists of matrices that analyse data sets according to the objective of the QFD process.

4.2b *Value stream mapping (VSM)*: Value stream mapping is a tool used to analyse the flow of materials and information currently required to bring a product or service to a consumer. It is nothing but the mapping of the current state of a process versus the future state of the process. The future state is the one to which we aim our progress. This technique originated at Toyota where it was known as 'Material and information flow mapping'. VSM is a general tool and can be applied to Design process by identifying different relevant fields such as

(i) Different departments involved in the process or cross-functional experts.
(ii) Various phases ranging of the process.
(iii) Flowcharts showing detailed activities.

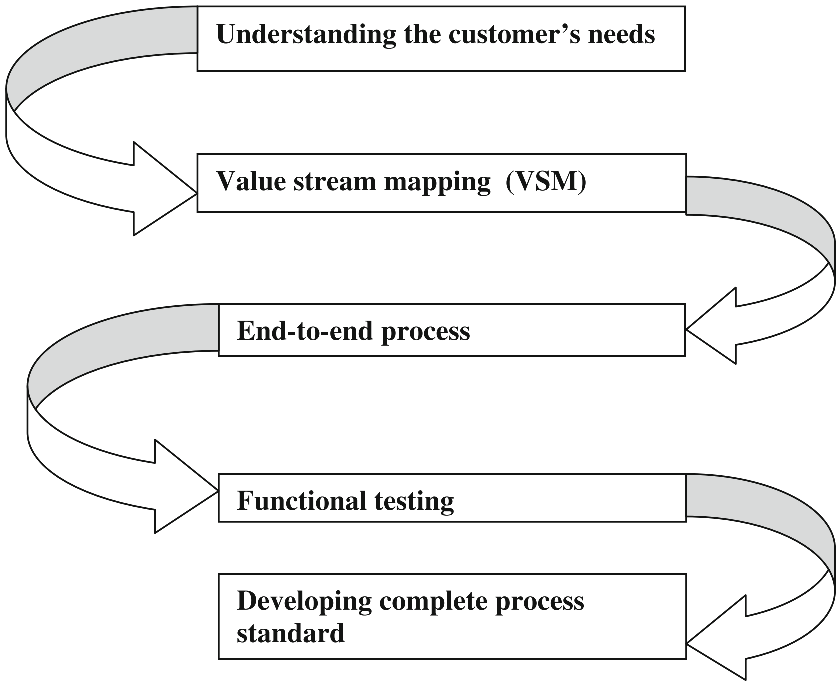

Figure 1. Stages of lean design process.

(iv) Standards for each activity (the future state).
(v) Timeline and resources fields.

4.2c *End-to-end process*: Leanness can be applied to the Design Process in two ways. First way can be considered by improving the technical processes related to the design of the product and second, by making the efforts of the human resources more efficient and effective.

Tools of technical perspective include:

(i) Finite Element Analysis (FEM) – It is a common tool (e.g., ANSIS, ABACUS, etc.) nowadays used by organizations for product design and analysis.
(ii) Material Selector – It consists of an exhaustive database of all manufacturing and industrial materials for selection of materials (e.g., Cambridge Material Selector).
(iii) DFMA (Design for Manufacturing and Assembly) – Modularity, an important tool in lean design, should be kept in mind while designing any product along with the consideration of manufacturability and assembly restrictions in lean design.

Tools of human perspective include:

(i) Visual boards identifying the exact scope of each expert or team involved in the design process.
(ii) An online website hosting the latest updates regarding the product. These updates maybe in terms of cancellation of some previous ideas or generation of any new ideas. This helps in reducing the effort wasted.
(iii) An online database of the product development.

4.2d *Functional testing*: Before launching the final in the market, a number of functional tests need to be performed on the product. If a manufacturer wants to do Wind-Tunnel Testing on his to be launched model, he does the testing on properly manufactured models and the amount of money and time wasted in this way is enormous. Now the same manufacturer can perform these tests in a fairly accurate manner through the help of software thus saving a lot of time and money. Therefore, the way of testing the products manufactured also plays an important role in deciding the overall time-to-market.

4.2e *Developing a complete process standard*: A well-performing organizations will always improve continuously by innovations but these innovations need to be documented well. This helps them in identifying the 'best standards' for every process rather than for every project. It is important for organizations to understand that for successful management of multiple projects, having process standards is more important than single project standards. The organization can have project standards in terms of drawings and designs for products that they have previously worked upon. Process standards can be the set of steps that must be involved schematically for the successful completion of the process. Organizations generally tend to consider every product as unique. So, for every new product they start from scratch which wastes a lot of time and resources. The first step for the organization would be to categorize its total range of products. So, whenever a new product is introduced, the organization can look up its category and decide various things instantaneously. This will immensely reduce the effort and the time that the organizations take in deciding the initial rough cost, risks and moreover, will also reduce the overall time-to-market.

4.3 *Lean design process assessment: The need for it*

The latter half of twentieth century witnessed a major shift in manufacturing practices from mass production to lean manufacturing. Any organization attempting to make a transition needs to first understand its standing in the journey towards leanness. Consequently there is a need for a comprehensive lean assessment system which would not only represent the present state of the organization but also provide valuable insights, as to how it can further improve its facilities. Identification of the parameters on which such a system would be based on would be the logical beginning. This will be followed by thorough validation of the system by applying it on industrial data. Hence, development of an efficient lean assessment system which would give the user a deeper understanding of key issues and help it in identifying problem areas and their potential solutions which are the need of present time.

Although some assessment systems have been developed in the field of manufacturing, there is a need to evolve a Lean Design Process Assessment System. Once an organization has started implementing the lean principles in their Design Process, there must be some way that should tell it 'To what extent they are Lean'. The basic idea is to provide a practical knowledge base or a new design tool for the organizations to enable them to further move towards Leanness. Applying leanness is not just a procedure but is a continuous improvement process. It is therefore, essential to have systems that could tell organizations the areas where they need to work upon to increase their leanness. With the increased awareness among the organizations regarding the lean approach, more and more organizations want to assess their lean extent.

The development of a general assessment system to judge the leanness in design process is the need of the today's world. One way could be to define the wastes in Design Process and find out to what extent these wastes exist in the system. More the wastes, less lean is the system. Like the eight wastes have been identified and defined in manufacturing, similar wastes need to be defined using the lean terminology in design process. These wastes should be defined such that the elimination of these wastes leads to Lean Design Process. A better way of doing this can be

(i) Identifying which wastes in lean manufacturing are applicable to Lean Design Process.
(ii) Identifying some more wastes that may be specific to Lean Design Process only and may have no mention in lean manufacturing.

5. Lean design of machine tool

Until now the application of lean concepts has been limited to manufacturing/material flow process of a product only. The lean manufacturing will utilize all the process and people oriented lean tools to produce a product, even if it is flat, and it will not be able to get the wastage out of the product itself. Also it does not care whether the actual product being made is lean in all aspects or not. It is at this stage the concepts of lean product design take a centre stage. In fact 70% of the cost of product, its functionality, time to manufacture and assembly, reliability, quality, customer satisfaction, operator-friendliness, etc. are all highly dependent on the design of product. Still the lean concepts have not yet been applied to the design of the product and the machine tools. The leanness in machine tool refers to the optimum static design aspects regarding proper loading and unloading system, producing better quality product with minimum cost and ease in manufacturing, assembly, maintenance, cleanliness and visual control. The most important aspect among these is the static design of machine tool. The conventional design is basically based on hit and trial method in which desired dynamic characteristics are achieved by making several prototypes. The disadvantage of this technique is that the actual design cycle takes a lot of time and many a times it ends up with over-designing of the product resulting in use of more material and thus increasing the cost of the product. Any existing machine tool can be assessed for its leanness by static analysis using a FEM package (ANSYS or ABAQUS) to avoid over-designing and reduction in the material used as well as identifying various parameters on which leanness of a machine tool depends.

In figure 2 (in the middle) a lean product (a drilling machine tool) is shown. Any deviation from this lean product would result in either failure or over-designing. Thus, due to lack of appropriate FEM analysis the product has failed in vibration as shown in figure on the left side. On the other hand, if extra material is added to increase the strength and to reduce vibration then the cost of machine would escalate due to the over-designing of the machine tool.

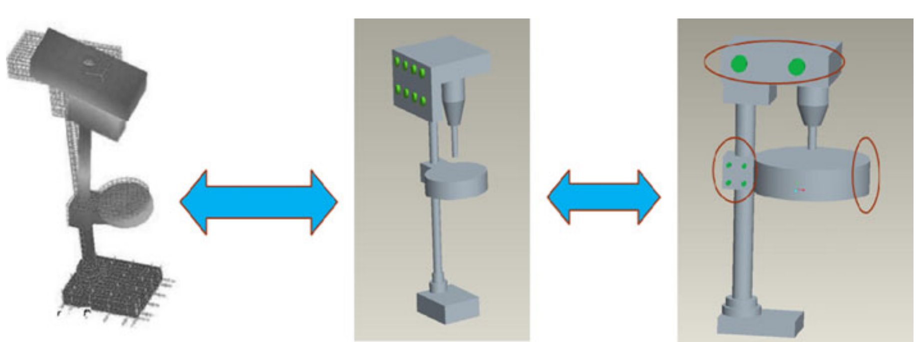

Figure 2. Lean machine tool (courtesy: Jain *et al* 2008).

5.1 *The need for lean machine tools*

Designing leanness into the machine tool will provide the following major advantages (Jain *et al* 2008).

(i) Increased productive time and reduced non-productive time of the machine.
(ii) Uses less material.
(iii) Reduces the design cycle time and hence product takes less time to come into the market.
(iv) Makes the machine more operator friendly.
(v) Makes machine tool more conventional for use.
(vi) Lean design will result in ease of assembling of the machine tool.
(vii) Lean design will result in ease of manufacturing of the machine tools.
(viii) Improves product quality and reliability.
(ix) Makes maintenance and cleanliness of machine more easy.
(x) Improves the loading and unloading system.
(xi) Changing of work piece becomes faster.

5.2 *The process of lean design of machine tool*

In the literature, much work is not reported on lean design of machine tools, but some work is visible at IIT Delhi on making the design lean by performing static analysis using a FEM package. Bais *et al* (2004) conducted studies on the dynamic stability of the drill machine by model updating. The model testing of drill machine was carried out using an instrumented impact hammer followed by updating the FE model to carry out the dynamic analysis. Bhaskar (2004) attempted to improve the dynamic stability of the machine tool to reduce the vibration level by using experimental modal analysis, model updating and structural dynamic modification methods to determine the change in dynamic characteristics as a result of certain design modifications. Also, in another study at IIT Delhi (Jain & Agrawal 2008) a mass reduction of 13.42% was reported through static consideration of lean design of drilling machine tool.

Figure 3 shows the process of lean design of machine tool. The literature survey reveals that a lot of experimental and mathematical model development work has been conducted by various researchers in the field of introducing leanness particularly in the vibration side of various

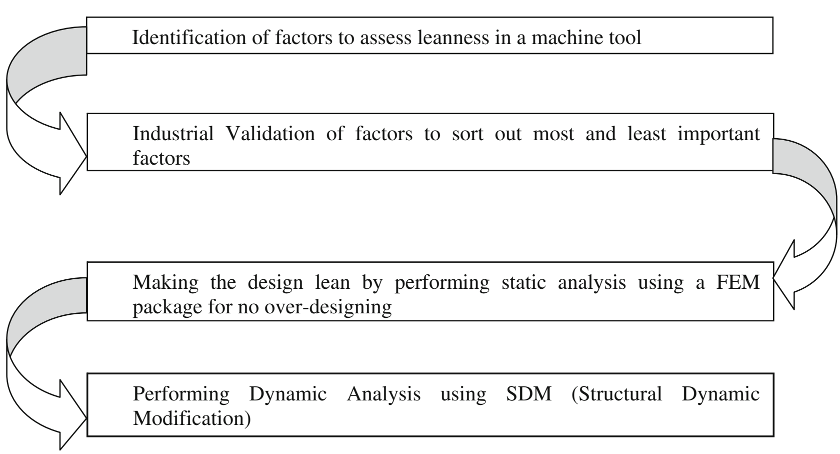

Figure 3. Process of lean design of machine tool.

beams, structures and machine tools (Modak *et al* 2005, Kundra 2004, Jain & Kundra (2004), Modak *et al* (2000, 2002a, b, c), Srivastava & Kundra (1998, 1993), Kundra & Nakra (1984)). According to Kundra (2004) the work is only at the laboratory stage and has not been extensively explored and adopted by the industry for the fear of increasing cost of vibration design of machine tools. However, the design process involves conducting modal testing of the machine tool experimentally without breaking the mechanical equipment followed by performing modification to the structure dynamically at the computer level itself. This will result in a lot of saving in time and cost and thus providing a competitive edge to the manufacturing organisation whosoever adopt this technology by designing this lean concept in machine tools.

6. Conclusion

In this paper, the evolution of leanness in manufacturing organisations from the middle of twentieth century till date has been reviewed and discussed. From the review it can be concluded that almost at saturation level work has been reported in the application and evaluation of lean principles to manufacturing systems with very little work evident in the area of introducing leanness in the design process leading to lean machine tools. A lot of leanness of the machine tool appears to be achievable by modern dynamic design technologies namely; Modal Testing, Finite Element Model Updating and Structural Dynamic Modification. There is a need to address and gradually resolve several research issues in the practical application of these processes of design with a focus on the machine tool. The scope for future work in this area is wide open.

One of the main conclusions drawn in the lean design process is to identify the factors that assess the leanness (wastage removal) in the product and machine tool followed by performing the static and dynamic analysis using a FEM package for no over-designing. It is also noticed that leanness has evolved over the years and decades and is still undergoing continuous evolution due to its inherently built dynamic concept of continuous improvement.

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References

Abdulmalek F A, Rajgopal J 2007 Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *Int. J. Production Economics* 107: 223–236

Acaccia G M, Callegar M, Michelini R C, Milanesio R, Molfino R M, Rossi A 1995 Pilot CIM implementation for lean engineering experimentation. *Computer Integrated Manufacturing Systems* 8/3: 185–192

Agarwal A, Shankar R, Tiwari M K 2006 Modelling the metrics of lean, agile and leagile supply chain: An ANP-based approach. *Eur. J. Operational Res.* 173: 211–225

Ahlstrom P 1998 Sequences in the implementation of lean production. *Eur. Management J.* 16(3): 327–334

Almannai B, Greenough R, Kay J 2008 A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies. *Robotics and Computer-Integrated Manufacturing* 24: 501–507

Andersson R, Eriksson H, Torstensson H 2006 Similarities and differences between TQM, six sigma and lean. *The TQM Magazine* 18(3): 282–296

Andrew Crowley 1998 Construction as a manufacturing process: Lessons from the automotive industry. *Computers and Structures* 67: 389–400

Bais R S, Gupta A K, Nakra B C, Kundra T K 2004 Studies in dynamic design of drilling machine using updated finite element models. *Mechanism and Machine Theory* 39: 1307–1320

Barker R C 1994 Production systems without MRP: A lean time based design. *Omega, Int. J. Mgmt. Science* 22(4): 349–360

Bhasin S, Burcher P 2006 Lean viewed as a philosophy. *J. Manufacturing Technol. Management* 17(1), 56–72

Bhaskar B D 2004 Studies on improvement on dynamic stability of a drilling machine. A study at IIT Delhi

Bhuiyan N, Baghel A 2005 An overview of continuous improvement: From the past to the present. *Management Decision* 43(5): 761–771

Braiden B W, Morrison K G 1996 Lean manufacturing optimization of automotive motor compartment system. In *Proceedings of 19th International Conference on Computers and Industrial Engineering* 31(1/2), pp. 99–102

Brandon G M, Morrison K R 1996 Transformation to lean manufacturing by an automotive component supplier. In *19th International Conference on Computers and Industrial Engineering* 31(1/2), pp. 95–98

Browning T R, Heath R D 2009 Reconceptualizing the effects of lean on production costs with evidence from the F-22 program. *J. Operations Management* 27(1): 23–44

Buyukozkan G, Derili T, Baykasoglu A 2004 A survey on the methods and tools of concurrent new product development and agile manufacturing. *J. Intelligent Manufacturing* 15: 731–751

Cagliano R, Caniato F, Spina G 2004 Lean, agile and traditional supply: How do they impact manufacturing performance? *J. Purchase and Supply Management* 10(4–5): 151–164

Crute V, Ward Y, Brown S, Graves A 2003 Implementing lean in aerospace - challenging the assumptions and understanding the challenges. *Technovation* 23: 917–928

De Meyer A, Wittenberg-Cox A 1992 *Creating product value: Putting manufacturing on the strategic agenda.* London: Pitman

Dennis F X M, Comm C L 2000 Developing, implementing and transferring lean quality initiatives from the aerospace industry to all industries. *Managing Service Quality* 10(4): 248–256

Detty R B, Yingling J C 2000 Quantifying benefits of conversion to lean manufacturing with discrete event simulation: A case study. *Int. J. Production Res.* 38(2): 429–445

Domingo R, Alvarez R, Peria M M, Calvo R 2007 Materials flow improvement in a lean assembly line: A case study. *Assembly Automation* 27/2: 141–147

Edward D A, Maleyeff J 2005 The integration of lean management and six sigma. *The TQM Magazine* 17(1): 5–18

Emiliani M L 2001 Redefining the focus of investment analysts. *The TQM Magazine* 13(1): 34–50

Emiliani M L 2004 Improving business school courses by applying lean principles and practices. *Quality Assurance in Education* 12(4): 175–187

Emiliani M L 2006 Origins of lean management in America: The role of Connecticut businesses. *J. Management History* 12(2): 167–184

Garg H, Singh R K, Rao P V M, Kulkarni M S 2008 *Lean concepts in design process*. Project Report, IIT Delhi

Herron C, Braiden P M 2006 A methodology for developing sustainable quantifiable productivity improvement in manufacturing companies. *Int. J. Production Economics* 104: 143–153

Herron C, Hicks C 2008 The transfer of selected lean manufacturing techniques from Japanese automotive manufacturing into general manufacturing (UK) through change agents. *Robotics and Computer-Integrated Manufacturing* 24: 524–531

Hines P, Francis M, Found P 2005 Towards lean product life cycle management. *J. Materials & Technol. Management* 17/7: 866

Hines P, Holweg M, Rich N 2004 Learning to evolve a review of contemporary lean thinking. *Int. J. Operations and Production Management* 24(10): 994–1011

Holweg Matthias 2007 The genealogy of lean production. *J. Operations Management* 25: 420–437

Houshmand M, Jamshidnezhad B 2006 An extended model of design process of lean production systems by means of process variables. *Robotics and Computer-Integrated Manufacturing* 22(1): 1–16

Hunt R, Poltrock S E 1999 Boeing operations fleet support: A case study in integrated workplace design. In *Proceedings of the second international workshop on cooperative buildings (CoBuild'99)*, Pittsburg, USA (October 1–2, 1999). Lecture Notes in Computer Science, Vol 1370, pp 4–21. Springer-Verlag, Heidelberg

Jain B, Agrawal P, Rao P V M, Kundra T K 2008 *Lean machine tools*. A Project Report, IIT Delhi

Jain J R, Kundra T K 2004 Model based online diagnosis of unbalance and transverse fatigue crack in rotor systems. *Mechanics Res. Commun.* 31: 557–568

Jaitly P, Mittal V, Rao P V M, Kulkarni M S 2008 *Development of a lean assessment system for the shop floor*. A Project Report, IIT Delhi

Jones C, Medlen N, Merlo C, Robertson M, Shepherdson J 1999 The lean enterprise. *BT Technology Journal* 17(4): 15–22

Katayama H, Bennett D 1996 Lean production in a changing competitive world: A Japanese perspective. *Int. J. Operations & Production Management* 16(2): 8–23

Kinnie N, Hutchinson S, Purcell J 1998 Downsizing: Is it always lean and mean? *Personnel Rev.* 27(4): 296–311

Krishnamurthy R, Yauch C A 2007 Leagile manufacturing: A proposed corporate infrastructure. *Int. J. Operations & Production Management* 27(6): 588–604

Kundra T K 2004 Vibration designing of machine tools. *Modern Machine Tools*, Jan 2004 issue, pp 38–44

Kundra T K, Nakra B C 1984 Mathematical modelling using harmonic excitation data. *J. Sound and Vib.* 96(l): 153–157

Lewis M A 2000 Lean production and sustainable competitive advantage. *Int. J. Operations & Production Management* 20(8): 959–978

Liker J K 1998 *Becoming lean*. Portland, Oregon: Productivity Press

Liker J K 2004 *The Toyota Way*. New Delhi: Tata McGraw Hill

Logendran R, Salmasia N, Sriskandarajah C 2006 Two-machine group scheduling problems in discrete parts manufacturing with sequence-dependent setups. *Computers & Operations Res.* 33: 158–180

Modak S V, Kundra T K, Nakra B C 2000 Model updating using constrained optimization. *Mechanics Research Communications* 27(5): 543–551

Modak S V, Kundra T K, Nakra B C 2002a Use of an updated finite element model for dynamic design. *Mechanical Systems and Signal Processing* 16(2–3): 303–322

Modak S V, Kundra T K, Nakra B C 2002b Comparative study of model updating methods using simulated experimental data. *Computers and Structures* 80: 437–447

Modak S V, Kundra T K, Nakra B C 2002c Prediction of dynamic characteristics using updated finite element models. *J. Sound and Vib.* 254(3): 44–467

Modak S V, Kundra T K, Nakra B C 2005 Studies in dynamic design using updated models. *J. Sound and Vib.* 281: 943–964

Monden Y 1998 *Toyota production system: An integrated approach to just-in-time*, 3rd edn. Norcross, Georgia: Engineering and Management Press

Motwani J 2003 A business process change framework for examining lean manufacturing: A case study. *Industrial Management and Data Systems* 1032/5: 339–346

Mynott C 2000 *Lean product development*. Northampton, UK: Westfield Publishing

Narasimhan R, Swink M, Kim S W 2006 *Disentangling leanness and agility: An empirical investigation*. *J. Operations Management* 24: 440–457

Papadopoulou T C, Ozbayrak M 2005 Leanness: Experiences from the journey to date. *J. Manufacturing Technol. Management* 16(7): 784–807

Prince J, Kay J M 2003 Combining lean and agile characteristics: Creation of virtual groups by enhanced production flow analysis. *Int. J. Production Economics* 85: 305–318

Rivera L, Chenb F F 2007 Measuring the impact of lean tools on the cost–time investment of a product using cost–time profiles. *Robotics and Computer-Integrated Manufacturing* 23: 684–689
Rubio S, Corominas A 2008 Optimal manufacturing–remanufacturing policies in a lean production environment. *Computers and Industrial Engineering* 55(1): 234–242
Sahoo A K, Singh N K, Shankar R, Tiwari M K 2008 Lean philosophy: Implementation in a forging company. *Int. J. Advanced Manufacturing Technol.* 36: 451–462
Shah R, Ward P T 2003 Lean manufacturing: context, practice bundles, and performance. *J. Operations Management* 21(2): 129–149
Shah R, Ward P 2007 Defining and developing measures of lean production. *J. Operations Management* 25: 785–805
Shahram Taj 2005 Applying lean assessment tools in Chinese hi-tech industries. *Management Decision* 43(4): 628–643
Shahram Taj 2008 Lean manufacturing performance in China: Assessment of 65 manufacturing plants. *J. Manufacturing Technol. Management* 19(2): 217–234
Shahram Taj, Lismar Berro 2006 Application of constrained management and lean manufacturing in developing best practices for productivity improvement in an auto-assembly plant. *Int. J. Productivity and Performance Management* 55(3/4): 332–345
Sohal A S, Egglestone A 1994 Lean production: Experience among Australian Organizations. *Int. J. Operations & Production Management* 14(11): 35–51
Spithoven A H G M 2001 Lean production and disability. *Int. J. Social Economics* 28(9): 725–741
Srivastava R K, Kundra T K 1993 Structural dynamic modification with damped beam elements. *Computers & Structures* 48(5): 943–950
Srivastava R K, Kundra T K 1998 Natural frequency constrained optimal structural modification using a sensitivity derivative of dynamically constrained mass and stiffness matrices. *J. Sound and Vib.* 211(3): 527–536
Tim Helton *Applying lean to the machine*. www.techsolve.org
Tony Bendell 2006 A review and comparison of six sigma and the lean organisations. *The TQM Magazine* 18(3): 255–262
Womack James, Jones D 1996 *Lean thinking: Banish waste and create wealth in your corporation*. New York: Simon and Schuster
Womack J P, Jones D T, Roos D 1990 *The machine that changed the world*. New York: Rawson Associates
www.leanvalue.com
www.etigroup.com
www.isiworld.net
www.strategosinc.com