Lean engineering performance measurement model

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Abstract

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Today, the application of lean principles is not limited to the shop floor: it is extended to the entire enterprise. Knowledge-based activities, in particular, product development, can significantly benefit from the application of lean principles. R&D intensive organizations such as aerospace have started to implement lean in their product development processes, however, the performance measurement systems that are in place are obsolete and do not promote lean goals and principles. These methods are not capable of measuring the benefits of adopting lean initiatives in the product development process. In this research, a lean engineering performance measurement (LEPM) model is developed that takes into account key lean principles and performance indicators and measures the performance of the engineering process from a lean perspective. This model was implemented in the engineering process of a case company to measure and promote lean initiatives.

Acknowledgements

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1 INTRODUCTION

In this chapter, first, a background review is presented. Then, the objectives and the methodology of the research are discussed. Finally, the outline of the thesis is provided in the last section.

1.1 Background

Lean, derived from the Toyota Production System (TPS), is a methodology that aims to increase value for all stakeholders while eliminating waste. The lean implementation process starts by identifying value, mapping the value stream (identifying required processing steps to deliver value to the customer, including both material and information flow), and continues to create a smooth workflow, establish pull (vs push) in the process, and seek perfection (Womack & Jones, 2003). The application of lean principles in manufacturing has shown to result in significant improvements and savings. This success has encouraged non-manufacturing industries as well to implement lean initiatives in their work processes to achieve the same results. Globalization, reduction in military markets and reduced civil aircraft orders resulted in loss of profit and the emergence of over-capacity in the aerospace market. Thus, aerospace companies also started to rethink their existing operations and adopted lean in their organizations. In the US, Lockheed Martin’s Aeronautics and Pratt & Whitney, and in the UK, BAE Systems, were among aerospace companies that started to adopt lean in their manufacturing operations (Crute, Ward, Brown, & Graves, 2003).

To remain competitive in this changing economy, companies must have better quality, advanced technology, and lower cost compared to their competitors; this characterizes a lean enterprise (Comm & Mathaisel, 2000). Major value creation and waste elimination is not achievable by the sole application of lean to the manufacturing process. Lean thinking must be fostered by the entire organization in order to achieve a long term lean enterprise (Liker & Morgan, 2006), and to be successful, an appropriate change strategy within the whole organization is required (Bhasin, 2011).

A significant portion of the value that is aimed to be delivered to the customer is created in the product development process, when the manufacturing process has not yet even started. It is in the product development process that the product (design specifications, materials to be used, etc.) and the processes required to manufacture and deliver the product to the final customers are defined (Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011). No matter how lean is the manufacturing process, a poorly designed product can never create value for the final customer. To create value, the characteristics of a product have to meet customers' demand (voice of the customer) and fulfill their requirements. Moreover, nearly 80% of a product's cost is determined during product design, before the start of the manufacturing process (Crute, Ward, Brown, & Graves, 2003; McManus, Haggerty, & Murman, 2005). Therefore, to accomplish significant benefits from lean applications, the entire enterprise must become lean and "the key is engineering" (McManus, Haggerty, & Murman, 2005).

Knowledge-based activities such as design, product development, and new product introduction (or generally speaking an engineering process) has great potential to benefit significantly from the application of lean principles (Baines, Lightfoot, Williams, & Greenough, 2006; Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011; Oehmen, et al., 2012). In product development, we deal with the most advanced products and engineering processes, however, we deal at the same time with the design process, which is one of the most wasteful engineering efforts (Oppenheim, 2004).

The engineering process suffers enormously from waste. Nevertheless, since in engineering we deal with a workflow (flow of information) that is invisible most of the time, as opposed to the visible physical flow of products (flow of material) in manufacturing, waste is neither transparent nor tangible as it is in manufacturing. For example holding unnecessary inventory (raw material, work in progress, and finished products) which is considered a major source of waste in the lean methodology, can easily be seen and quantified in a manufacturing plant by taking a walk in the shop floor. Inventory in manufacturing is "physically and financially visible" (Baines, Lightfoot, Williams, & Greenough, 2006). However, in product development, inventory (which is in the form of information about product specifications) is hidden, thus, there is a need to make it transparent and quantifiable so it could be targeted for improvement.

From a lean perspective, all work activities are classified into one of the three following categories: 1) value-added (VA): activities that create value for stakeholders, 2) required non-value-added (RNVA): activities that do not create any value but are unavoidable and should be minimized, or 3) non-value-added (NVA) activities: activities that do not create any value and should be eliminated (Womack & Jones, 2003). In product development a poor performance can waste resources, time, information/knowledge, opportunity/potential, money/invest, and motivation of an organization (Bauch, 2004).

Large-scale engineering programs are one of the most challenging activities for any organization to manage. U.S. Department of Defense engineering development programs exceed extensively their budgeted cost and schedule. The largest 96 engineering programs in total incurred a roughly 300 billion dollars of added cost and incurred an average of 2 years of schedule overrun (Oehmen, et al., 2012).

McManus, Haggerty, and Murman (2005) emphasize the inefficiency of existing engineering processes indicating that a time card hour survey shows that only 31% of engineering effort is value added, while, 40% of it is pure waste (non-value added), and the remaining 29% is necessary waste (required non-value added) (see Figure 1-1 a). Adding the tracking of engineering work packages shows that 62% of the time tasks are idle in the system (see Figure 1-1 b) (75-90% idleness in the bottleneck processes). Combining the data as depicted in Figure 1-1 c, one can conclude that only 12% of the time a task undergoes value-added activity (McManus, 2005).

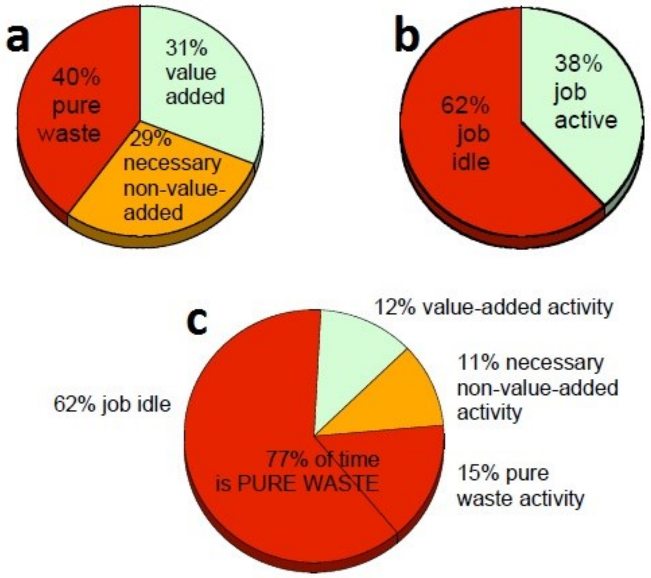


Figure 1-1 Waste in engineering process (McManus, 2005)

Over the decades, there has been an evolutionary shift from mass production to a mass customization dominant market where the traditional stage gate product development process is no longer the solution to success. Rapid progression of technology requires a minimized time to market (product development cycle), mass customization of products with higher complexity and flexibility and lower sales volumes call for lower development costs, and products having shorter lifecycles leave no space for failure, requiring higher quality. Today, companies need to continuously improve their product development performance on time, cost, and quality dimensions to be able to survive in the market (Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011). Implementing lean principles in the product development process is a solution that offers shorter development cycles, accelerated time to market, reduced development cost, improved manufacturability and quality of products, and fewer production start-up problems (Karlsson & Åhlström, 1996).

About 60–90% of the total time charged to research & development tasks in aerospace and defense programs is waste (Oppenheim, 2004). This waste can be minimized by applying lean to product development process in the aerospace sector (Baines, Lightfoot, Williams, & Greenough, 2006). Research conducted by UK Lean Aerospace Initiative (UK LAI) supports the benefits of applying lean principles at different process levels to aerospace engineering processes in both large and SME's (Haque, 2003).

Oehmen et al. (2012) report successful engineering programs adopt more lean enablers and implement them more frequently in their program which lead to an improved overall performance compared to unsuccessful engineering programs (Figure 1-2).

Kerssens-van Drongelen and Cooke (1997) state that "performance measurement is at the heart of any (R&D) quality management system". Without a performance measurement system, managers cannot effectively determine their current state of performance, thus, setting new targets and planning future states would be a much more complex task, especially in product development environment where uncertainty and risk are at the highest level. Without a performance measurement system, key questions like “how well are we doing?”, “what have we learned?”, and “what should we do in the future?” remain unanswered (Tatikonda, 2008).

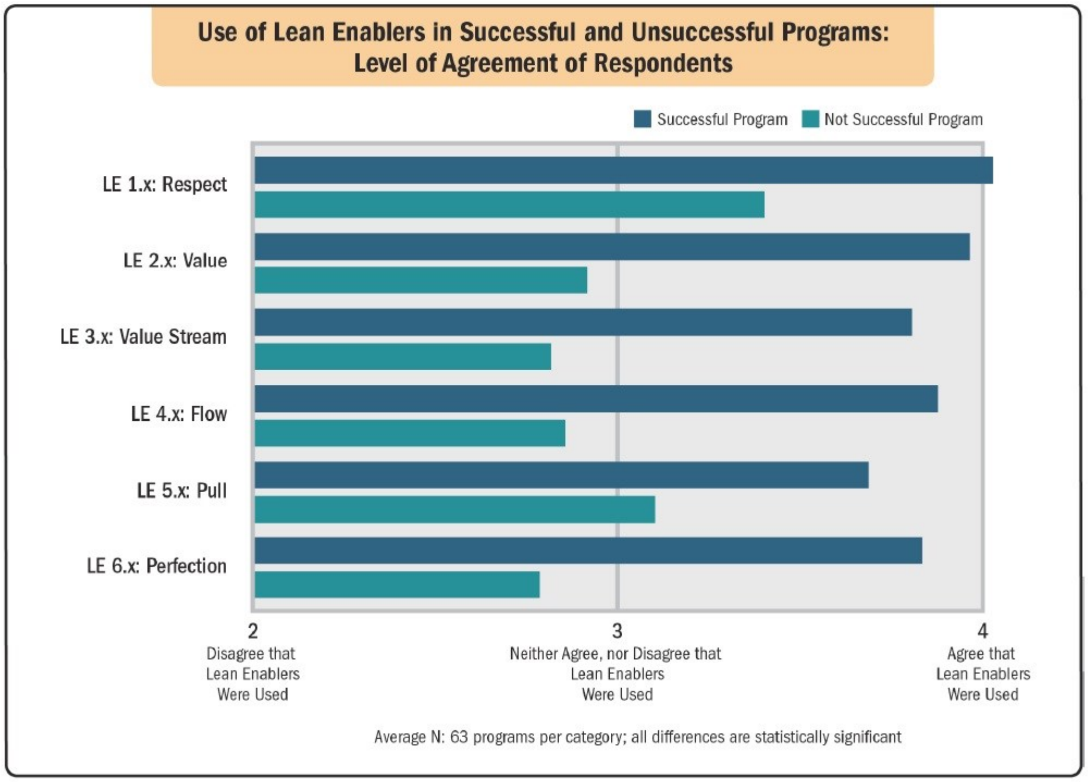


Figure 1-2 Use of lean enablers in engineering programs (Oehmen, et al., 2012)

Performance is a function of efficiency and effectiveness. A performance measurement system comprises a set of performance measures to quantify both the efficiency and effectiveness of actions. (Neely, Gregory, & Platts, 2005).

The need for the development of an effective performance measurement system for product development arose during 1990s, when market changes occurred. A performance measurement system that could evaluate efficiency and effectiveness of research and development process (R&D) and its alignment with strategies was needed (Chiesa, Frattini, Lazzarotti, & Manzini, 2009). Increased competitiveness, globalization, higher demand of customized products, reduced product lifecycles, rapid changes in customer requirements and market trends, higher degree of technological tools, higher speed of technology evolution, more robust standards, and profitability are amongst characteristics of the modern product development environment which call for an effective performance measurement system to measure and monitor product development process (Kerssens-van Drongelen, Nixon, & Pearson, 2000).

Achieving continuous improvement and seeking perfection is a lean principle and also the ultimate goal of any organization that wants to survive and succeed in this competitive environment. Measurement plays a vital role in any continuous improvement method. It is impossible to adopt and benefit from process improvement methods such as PDCA (Plan, Do, Check, Act) or DMAIC (Define, Measure, Analyze, Improve and Control) without appropriate data collection, measurement and analysis which are the foundational activities (constituting check phase in PDCA or measure phase in DMAIC) in these methods. Therefore, in order to coordinate, integrate, and manage all effort within product development process to transform into a lean engineering environment, once the organization has defined its goals, it is important to implement a performance measurement system that can identify the gap between current and desired performance states and track the progress towards achieving lean goals.

1.2 Objectives and methodology

This research aims to develop a performance measurement model that can evaluate the effects of adopting lean in the engineering process. The model presented here is based on the model developed by Beauregard, Thomson, and Bhuiyan (2008) for an aerospace engineering company. The focus is to improve the model in terms of measurement and applicability in order to implement it in any type of engineering work regardless of the industry or size of the organization, to effectively measure and promote lean engineering performance.

First, lean principles, tools, technique, and goals in product development were studied. Second, literature on requirements of a performance measurement model for product development and relative work in the field of lean product development performance measurement were examined and gaps and opportunities were identified. Third, the engineering effort was analyzed in order to identify hidden waste in engineering process and enable differentiating between value-added, non-value-added, and required non-value-added elements of engineering effort. Finally, the model developed by Beauregard, Thomson, and Bhuiyan (2008) was analyzed and modified in order to improve its performance measurement effectivity and extend its applicability.

Model equations are modified to improve the model. To measure performance, total waste incurred while processing tasks in a value stream is taken into account while the original model takes into account waste for completed tasks. New performance measures are developed that account for wasteful aspects of engineering work which are unique to the engineering process and had received no attention in the existing publications. Moreover, a decomposition chart is developed for available working time so as to enable the discrimination of waste from value-added part of engineering effort.

1.3 Thesis organization

The research presented in this thesis is organized in six chapters. In second chapter, the literature on the lean product development is reviewed. In third chapter, existing literature and work in the field of lean performance measurement is discussed and the gaps and opportunities are identified. The lean engineering performance measurement model developed in this research is presented in chapter four. Chapter five provides the results of implementing the model in an engineering company to measure lean engineering performance. Finally, in chapter six, conclusions, limitations, and opportunities for future research are presented.

2 LITERATURE REVIEW

In this chapter, a review of the lean product development literature is presented.

2.1 Implementing lean in the product development process

Lean product development is capable of addressing emerging issues in the market. However, the application of lean to the product development process has been lacking (Baines, Lightfoot, Williams, & Greenough, 2006; Haque, 2003; Haque & Moore, 2004). This can be partly due to the fact that application of lean principles to functions other than manufacturing, where we deal with low volume, highly customized products, is a challenge. However, this lower volume may enhance the achievement of a single piece flow which is one of the five lean principles (Crute, Ward, Brown, & Graves, 2003).

In order to successfully implement lean, traditional systems, practices, and behavior must be changed within the organization (Baines, Lightfoot, Williams, & Greenough, 2006). In the lean transformation process, speed of change and results are not the same in every company (Soriano-Meier & Forrester, 2002). Factors such as change strategy (targeted vs. holistic), company culture, product focus, senior management commitment and consistency of focus, time and space for performance improvements (Crute, Ward, Brown, & Graves, 2003), piecemeal adoption of lean components, and contextual factors (Fullerton & Wempe, 2009) cause variations in performance effects.

The problem with applying lean to firms operating in high variability, low volume environments arises when a tool-based approach to lean is taken (Lander & Liker, 2007). Many companies that had success in lean manufacturing, adopt only some lean tools in their product development process as a short term solution (Liker & Morgan, 2006). According to Browning (2000), there are two approaches to getting lean: liposuction approach and exercise approach. In the liposuction approach, the emphasis is on removing non-value-added activities by performing only some kaizen events. In the exercise approach, the focus is on maximizing value by ensuring the quality of input as well as the process itself, so that the value of the product is maximized.

Adopting some lean tools such as Kanban, Heijunka, 5S, and poke-yoke, will not assure continuous improvement. Results from such discrete application of lean tools are not significant (Baines, Lightfoot, Williams, & Greenough, 2006). Rather than applying some lean tools and techniques in a piecemeal manner, lean should be adopted in a holistic manner (Crute, Ward, Brown, & Graves, 2003; Karlsson & Åhlström, 1996; Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011). Implementing some lean techniques is not enough for accomplishing lean product development (Karlsson & Åhlström, 1996). This tool-based approach to lean is more common in western organizations that view lean as a set of tools and techniques. In Japanese companies, lean is treated as a culture and philosophy that is applied throughout the whole organization (Baines, Lightfoot, Williams, & Greenough, 2006). Sole focus on waste removal cannot identify root causes of waste. To maximize value, no matter how lean the activities, the structure of product development (the sequencing and coordination of activities and deliverables) should also become lean (Browning, 2000).

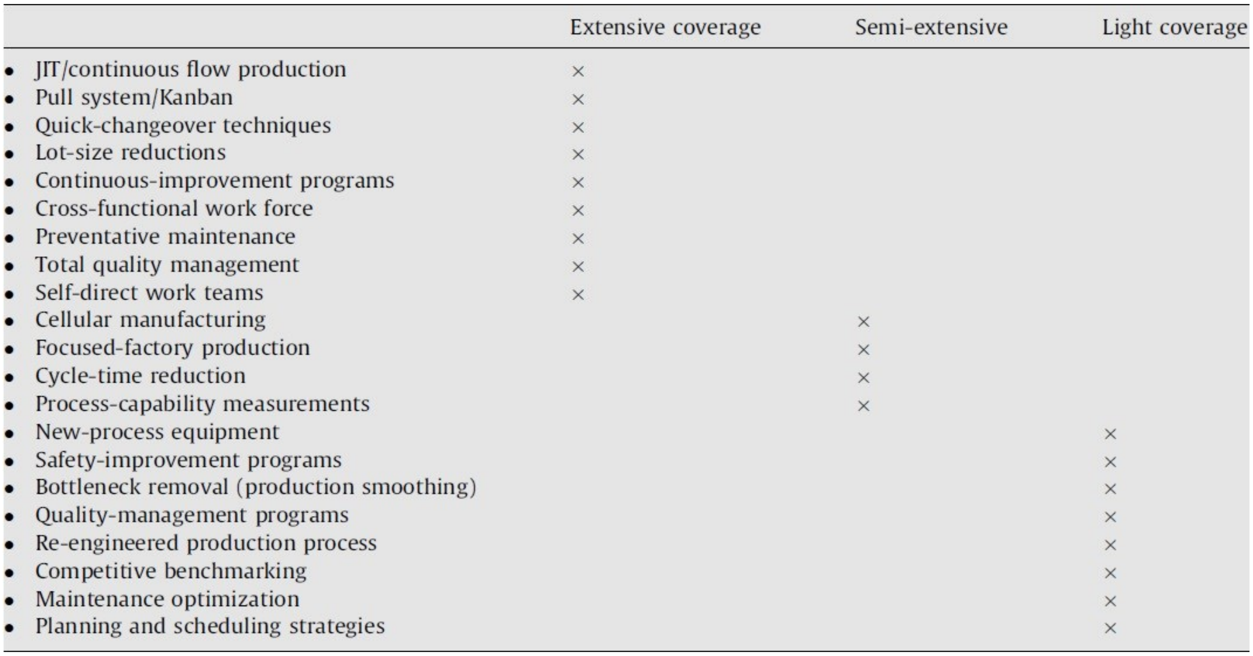
Bhasin (2011) stresses the importance of lean implementation as a philosophy. He argues that organizations that implement lean as a philosophy have better overall performance with respect to those only implementing some lean tools. Fewer barriers, wider application of lean across the organization, wider tool application, an appropriate culture, and lean change strategy are among common characteristics of such organizations.

Shah and Ward (2003) did research to examine the effects of three contextual factors namely plant size, plant age and unionization status on the implementation of 22 lean manufacturing practices. They combined those 22 practices in order to form four lean bundles of interrelated lean practices, i.e. just-in-time (JIT), total quality management (TQM), total preventive maintenance (TPM), and human resource management (HRM). They studied the effects of implementing such bundles on operational performance. Based on the literature review, they developed the following four propositions to test: 1) unionized plants are less likely to implement lean manufacturing practices than nonunionized or partially unionized plants; 2) older plants are less likely to implement lean manufacturing practices than newer plants; 3) large manufacturers are more likely to implement lean practices than small manufacturers; 4) implementation of lean bundles, each representing groups of related lean practices, will have a positive impact on operational performance. They empirically examined these propositions using sample data from Industry Week's Census of Manufacturers.

Shah and Ward (2003) revealed that contextual factors in an organization such as plant size, plant age and unionization status significantly influence the implementation of lean practices but to different extents, where, the influence of plant size seems to be more substantial than others. Their results reveal that implementation of lean practices as lean bundles contribute substantially to the operating performance which supports the previously discussed studies regarding systematic use of lean practices. They argue that regardless of contextual factors, companies that implement lean practices in bundles have performance advantage over those that implement individual lean practices.

Bayou and Korvin (2008) classified lean practices reported by Shah and Ward (2003) into following three categories: extensive, semi-extensive and light coverage (see Table 2-1) based on the number of their coverage in the industrial and management literature from 1977 to 1999.

Table 2-1 Coverage of lean practices in the industrial and management literature 1977–1999 (Bayou & Korvin, 2008)



	Extensive coverage	Semi-extensive	Light coverage
• JIT/continuous flow production	×		
• Pull system/Kanban	×		
• Quick-changeover techniques	×		
• Lot-size reductions	×		
• Continuous-improvement programs	×		
• Cross-functional work force	×		
• Preventative maintenance	×		
• Total quality management	×		
• Self-direct work teams	×		
• Cellular manufacturing		×	
• Focused-factory production		×	
• Cycle-time reduction		×	
• Process-capability measurements		×	
• New-process equipment			×
• Safety-improvement programs			×
• Bottleneck removal (production smoothing)			×
• Quality-management programs			×
• Re-engineered production process			×
• Competitive benchmarking			×
• Maintenance optimization			×
• Planning and scheduling strategies			×

Oehmen et al. (2012), in a joint study with MIT, the Project Management Institute (PMI) and the INCOSE Community of Practice on Lean in Program Management, made up of select subject matter experts from industry, government, and academia, classify engineering management problems into ten major categories: 1) firefighting, reactive (vs proactive) execution of engineering programs, 2) lack of a clear definition of stakeholders' requirements, 3) value chain is not properly aligned and coordinated, 4) local optimization of processes (vs overall value stream optimization), 5) lack of a clear definition of roles, responsibilities, and accountability, 6) program culture, team competency, and knowledge are poorly managed, 7) poor scheduling, 8) use of ineffective performance metrics, 9) reactive (vs proactive) risk management, and 10) improper program acquisition and contracting practices. They argue that lean practices can be implemented to correct and prevent such problems and identify the best in class lean practices to address such engineering management problems. They propose 43 lean enablers with 286 subenablers and categorize these practices into 6 categories referring to the lean principle that the practice aims to promote (sixth principle used in their categorization is respect for people).

2.2 Lean product development

Liker and Morgan (2006) stress that lean is not application of some tools as a short-term solution; instead, it should be systematically adopted in the entire organization to create a learning culture. They define lean product development as a system that integrates people, process and technology. They study the Toyota Product Development System and identify 13 fundamental principles for a lean product development and classify these principles into process, people, and technology categories (Table 2-2).

Table 2-2 Lean product development principles (Liker & Morgan, 2006)

Process principles	1. Establish customer-defined value to separate value-added from waste. 2. Front-load the product development process to explore thoroughly alternative solutions while there is maximum design space. 3. Create a level product development process flow. 4. Utilize rigorous standardization to reduce variation, and create flexibility and predictable outcomes.
People principles	5. Develop a chief engineer system to integrate development from start to finish. 6. Organize to balance functional expertise and cross-functional integration. 7. Develop towering competence in all engineers. 8. Fully integrate suppliers into the product development system. 9. Build in learning and continuous improvement. 10. Build a culture to support excellence and relentless improvement.
Technology Principles	11. Adapt technologies to fit your people and process. 12. Align your organization through simple visual communication. 13. Use powerful tools for standardization and organizational learning.

According to Karlsson and Åhlström (1996), lean product development is a system of interrelated techniques including supplier involvement, simultaneous engineering (concurrent engineering), use of cross-functional teams, integration (as opposed to coordination) of various functional aspects of the project, use of a heavyweight team structure, and strategic management of projects. They carry out a longitudinal study to identify hindering and supporting factors to implementation of lean in product development process.

McManus, Haggerty, and Murman (2005) define goals of lean engineering as creating the right products, with effective lifecycle and enterprise integration, using efficient engineering processes and explain a number of lean engineering techniques for achievement of each goal. They also discuss the results of applying those lean engineering techniques to aerospace programs.

In an effort to apply lean to engineering work of the product development process, Oppenheim (2004) developed a general framework based on lean principles called lean product development flow (LPDF). To create smooth flow throughout the engineering value stream, he proposes parsing the engineering work into short and equal takt periods of 1 week, each ending in an integrative event. This type of scheduling requires dynamic allocation of resources depending on the effort required for each task. Figure 2-1 depicts the lean product development flow framework. By splitting traditionally long and continuous engineering work into shorter and equal subtasks, the author attempts to minimize the batch size in product development as in the case of lean production. He argues shorter takt periods and frequent review events would reduce waste, error discovery time, and information churning in product development.

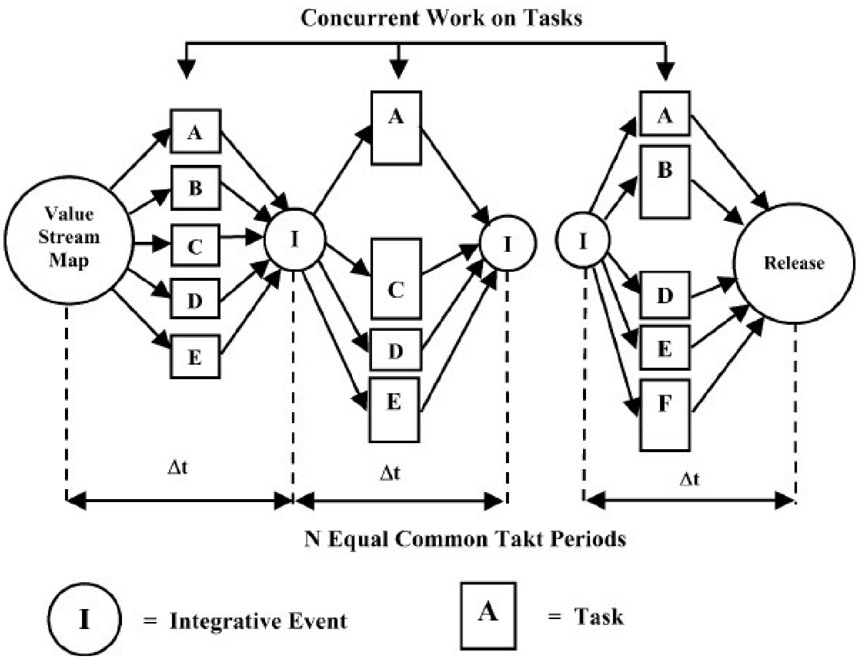


Figure 2-1 Lean product development flow framework (Oppenheim, 2004)

Oppenheim (2004) recommends the use of the LPDF framework in smaller product development programs where engineering work is based on a high degree of legacy knowledge and mature technologies where the feasibility of the program is not in question. He defines the value of lean product development flow as delivering quality product (design) that meets requirements of all stakeholders within short schedule and at minimum cost. This reduced cost and schedule can be achieved by eliminating waste in the product development process.

Oppenheim (2004), McManus, Haggerty, and Murman (2005), and McManus (2005) all suggest that in order to make the lean product development workflow more predictable in terms of time, effort, quality, and cost and also to mitigate the risk resulted by uncertainty associated with high risk research work (that affects PD cost and time), such high risk activities should be separated from the main product development value stream.

There is not yet a consensus on the definition of lean in product development. For example, a shift from focusing on waste reduction towards focusing on value creation is emerging in publications (Baines, Lightfoot, Williams, & Greenough, 2006). Browning (2000) points out that in product development, lean is not minimizing cost, cycle time, or waste, instead, lean is maximizing value for the customers within the constraints of all stakeholders. He argues that value in product development is not necessarily increased by removing activities, sometimes more activities are required to increase value. He indicates that in the product development process, producing useful information creates value and due to the iterative nature of product development activities, the most important factor to add value is getting the right information in the right place at the right time. He adds that to deliver value which is a function of product performance, affordability, and availability, a lean product development process is required which can affect all these three dimensions.

Hoppmann, Rebentisch, Dombrowski, and Zahn (2011) argue that existing definitions of lean product development are not consistent and assert that current empirical research in this area is weak. They define lean as a system that comprises a set of highly interrelated and interdependent components. To integrate existing work on lean product development into a consistent framework, they use content analysis to study 27 lean product development publications and derive 11 major components for lean product development as follows: 1) strong project manager, 2) specialist career path, 3) workload leveling, 4) responsibility-based planning and control, 5) cross-project knowledge transfer, 6) simultaneous engineering, 7) supplier integration, 8) product variety management, 9) rapid prototyping, simulation and testing, 10) process standardization, and 11) set-based engineering.

2.3 Summary

From the literature review it is clear that to achieve a lean product development process, a holistic view of lean should be taken (Karlsson & Åhlström, 1996; Browning, 2000; Crute, Ward, Brown, & Graves, 2003; Oppenheim, 2004; McManus, Haggerty, & Murman, 2005; Baines, Lightfoot, Williams, & Greenough, 2006; Lander & Liker, 2007; Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011). To make the transition from a traditional stage gate product development process to a lean process, a number of tools and techniques have been developed and introduced over the years. Nonetheless, the remaining issue is selecting the appropriate ones and adapting them for implementation in the lean transformation process and evaluating the effect of such implementation on product development performance in order to measure the progress achieved towards leanness. In order to successfully apply lean especially to a new environment as engineering, a principle-based approach should be taken. Lean should be understood as a socio-technical system and the progress made should be measured to be consistent with its principles (Lander & Liker, 2007). Therefore a model capable of measuring performance of product development process with respect to lean principles is required.

3 LEAN PERFORMANCE MEASUREMENT

In this chapter, a review of the research in the field of lean performance measurement is presented and gaps and opportunities are identified and discussed.

3.1 Performance measurement system for product development

A number of researchers studied the design of a performance measurement system for the research and development process and identified the challenges associated with it. Product development environment has high level of uncertainty, risk, and fuzzy, delayed, intangible, and non-repetitive outcomes which make performance measurement a challenging activity (Chiesa & Masella, 1996; Brown & Svenson, 1998; Kerssens-van Drongelen, Nixon, & Pearson, 2000; Driva, Pawar, & Menon, 2001; Mascarenhas Hornos da Costa, Oehmen, Rebentisch, & Nightingale, 2014).

Kerssens-van Drongelen, Nixon, and Pearson (2000) defined the following factors as problems associated with designing a performance measurement system for R&D: complexity of separating and identifying the contribution of R&D department (apart from other functions) to company performance, R&D outputs being intangible and hard to quantify, the difficulty of identifying exact relations between R&D final outcomes, intermediate outputs, and inputs, the delay between the end of R&D efforts and recognizing its outcome in the market, determining the right metrics for measurement and the right standards to measure performance against, and the acceptance of such systems in an R&D environment.

Kuczmarski (2001) asserts that having a great number of metrics, excessive concentration on the outcomes of the process, irregular measurement of metrics, focusing more on reducing costs rather than increasing value, lack of a learning culture and the existence of a blame culture in the company will result in the failure of the implementation of a performance measurement system in innovative based activities.

As reported by Meyer, the following features should be considered in the design of a performance measurement system: 1) the primary objective of the measurement should be providing engineers with information to improve their performance (and not the managers), 2) engineers should be involved in the design of their own performance measurement system, 3) metrics should be able to measure cross functional process performance, and 4) having too many metrics should be avoided (as cited in Parry & Turner, 2006).

According to the literature review conducted by Chiesa, Frattini, Lazzarotti, and Manzini (2009), a performance measurement system for R&D comprises five major elements namely: 1) measurement objectives, 2) dimensions of performance, 3) indicators with which performance dimensions are measured, 4) structure (control objects whose performance is measured), and 5) measurement process (measurement frequency and standards). These elements, illustrated in Figure 3-1, are highly interconnected and interdependent in their design. For example, a change in the objective can affect measurement frequency and analysis process (Kerssens-van Drongelen & Cooke, 1997).

Identifying the objectives of measurement is the predominant step for designing an R&D performance measurement system. Designs of other elements are highly affected by the objectives selected (Kerssens-van Drongelen & Cooke, 1997; Chiesa, Frattini, Lazzarotti, & Manzini, 2009). Diagnosing activity to support decision making, motivating personnel, enhancing communication and coordination, learning, reducing R&D risks and uncertainty, and improving R&D performance are among significant objectives of R&D performance measurement systems (Chiesa, Frattini, Lazzarotti, & Manzini, 2009). Objectives that are implemented in different functions of an organization must coordinate and reflect the overall strategy of the organization, otherwise, while each function tries to improve their performance, conflict may arise between functions and overall performance can be affected (Neely, Gregory, & Platts, 2005).

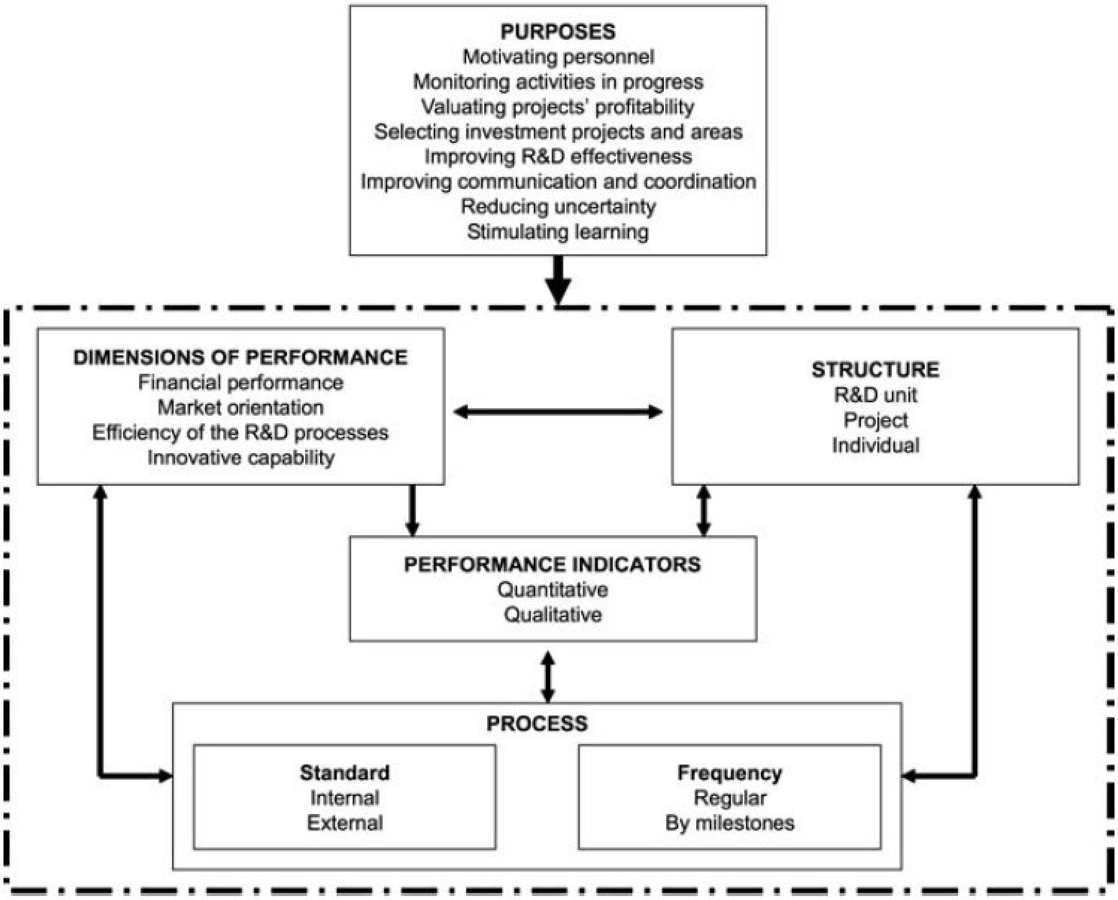


Figure 3-1 Elements of a performance measurement system for R&D (Chiesa, Frattini, Lazzarotti, & Manzini, 2009)

Performance criteria of a performance measurement system must: reflect the objectives of the measurement and strategies of the organization, enable benchmarking, have clear purpose and data collection and calculation method, be under control of the evaluated controlled objects, be objective rather than subjective, and be selected by involving people influenced by measurement (Neely, Gregory, & Platts, 2005).

Performance can be measured in four dimension as follows: 1) financial, accounts for profitability of R&D, 2) market orientation, refers to conformance of R&D deliverables to voice of customers, 3) efficiency, measures performance of R&D in terms of time, effort, and cost in the process of delivering outputs, and 4) innovative capability, evaluates knowledge developed by R&D (Chiesa, Frattini, Lazzarotti, & Manzini, 2009).

Identification of the right performance measures will enhance measurement implementation since they can provide enhanced visibility, a change of attitude, and a clearer customer oriented focus for employees and managers (Crute, Ward, Brown, & Graves, 2003). According to Maskell, performance metrics of world class manufacturing companies all have the following primary features in common: metrics are aligned with manufacturing strategy, non-financial metrics are included, different measurement methods are used to suit different areas of application, metrics are easy to use and provide fast feedback, metrics are updated, instead of a focus on monitoring, metrics are implemented to improve performance (as cited in Parry & Turner, 2006).

In a performance measurement system, metrics can be qualitative, quantitative, or a combination of the two. In terms of accuracy, reliability, and comparability, quantitative methods are more effective. Qualitative measurements are affected by the subjectivity of the person executing the evaluation, therefore, results can be highly subject to personal preference and bias (Kerssens-van Drongelen & Cooke, 1997; Tatikonda, 2008; Chiesa, Frattini, Lazzarotti, & Manzini, 2009). Hence, qualitative metrics should be used in balance with quantitative metrics to reduce such side effects while sustaining the ability to evaluate unmeasurable dimensions of performance in a product development environment (Chiesa, Frattini, Lazzarotti, & Manzini, 2009).

Metrics selected for performance measurement should suit the measurement objective as well as other components of the performance measurement system as these components are highly interdependent. To facilitate metric selection, Kerssens-van Drongelen, Nixon, and Pearson (2000) developed a taxonomy for R&D metrics using a cubic model and positioned metrics that were mentioned in existing industrial R&D publications. Criteria used for categorization of metrics are: time span covered (metrics referring to performance in the distant past, recent past, near future, or far future), performance aspects (metrics referring to general, quality, innovativeness, timeliness, cost, or quantity aspect), and the closeness to organizational goals (metrics referring to inputs, activities, outputs, or outcomes).

Financial performance metrics are more popular than non-financial metrics (Driva, Pawar, & Menon, 2001; Kerssens-van Drongelen, Nixon, & Pearson, 2000). Financial metrics are more effective to show profitability from a high level perspective, but these measures do not reflect efficiency level utilized to achieve such profit and due to the nature of new product development activities, these indicators are lagging. In order to be able to fully benefit from performance measurement, different types of metrics should be linked and used in combination, which seems to be lacking in existing work in this area (Driva, Pawar, & Menon, 2001; Soriano-Meier & Forrester, 2002). This combination must focus on the product development process as well as its outputs to enable the measurement of tangible and intangible organization assets (Haque & Moore, 2004).

A performance measurement system must link organizational strategies at the corporate level to actions at the operational level. Parry and Turner (2006) argue that financial measures are lagging, outcome focused, and can be misinterpreted. These indicators are not sufficient to measure business performance and they cannot promote lean thinking. Use of a financial metric such as return on investment to evaluate product development process performance has its own complexities. It is difficult to assess the amount of profit that results from the product development process as a separate function. Moreover, this profit does not occur at the end of the product development process and there is a delay until this profit is made and the results are available for performance measurement. It may take years to launch a product into the market after it is developed (Chiesa & Masella, 1996; Kerssens-van Drongelen & Cooke, 1997). To improve performance measurement, a combination of financial and non-financial measures must be used (Parry & Turner, 2006; Fullerton & Wempe, 2009).

Defining correct norms and standards to measure performance against is a big challenge, especially in R&D (Kerssens-van Drongelen & Cooke, 1997; Chiesa, Frattini, Lazzarotti, & Manzini, 2009). R&D activities are classified as a project type of work, a non-repetitive process which delivers a unique output, compared to manufacturing work that is classified as operation type of work and is an ongoing repetitive process aimed to produce the same output each time. This adds to the complexity of defining proper standards to enable benchmarking as well as defining new targets in this environment. However, in product development as opposed to basic research, most of the processing steps are based on the legacy knowledge and are known beforehand (Kerssens-van Drongelen & Cooke, 1997).

Performance standards can either be internal or external. Internal standards can be targets set for performance or be a previous established performance derived from performance records

(Chiesa, Frattini, Lazzarotti, & Manzini, 2009). External standards can be industry standards or best practices from market competitors that are used for benchmarking (Kerssens-van Drongelen & Cooke, 1997). A high amount of complexity, risk, uncertainty, variability, diversity, and uniqueness of products and services in R&D environment together with the lack of interest of firms to share information with the outside world (due to sensitivity of information and confidentiality reasons) make defining external standards to measure performance against very complex and rare. Therefore, companies tend to use internal standards to benchmark performance (Driva, Pawar, & Menon, 2000; Chiesa, Frattini, Lazzarotti, & Manzini, 2009; Driva, Pawar, & Menon, 2001). Comm and Mathaisel (2000) define lack of time, lack of resources, and the existence of a competitive market as benchmarking barriers. Proper performance measurement and documentation of performance data enables development of appropriate standards and improves accuracy of future forecast of performance (Kerssens-van Drongelen & Cooke, 1997).

Measurement frequency depends on key elements of a performance measurement system as well as the level at which performance is measured, resources that are required for measurement, and the cost associated with measurement. For example, Measurements at process level are done more frequently than the measurements at organizational level. Measurements are usually carried out before reaching to or at the project’s milestones or on a regular periodic basis (e.g. weekly, monthly, quarterly, and yearly) (Chiesa, Frattini, Lazzarotti, & Manzini, 2009).

In a study to examine the differences between the performance measurement systems in research (basic and applied research) and in new product development, Chiesa, Frattini, Lazzarotti, and Manzini (2009) found no significant difference between the elements (monitored performance, control objects, frequency, indicators, and standards) of the two types of systems based on their empirical research. However, they stress that personnel motivation seems to be of higher importance as an objective for the research activities and project profitability measurement seems to be of higher importance as an objective for the development activities. Kerssens-van Drongelen and Cooke (1997) indicate that research and development activities are different in nature, but report no differences between the measurement methods in applied research and in product development based on their empirical research.

Kerssens-van Drongelen, Nixon, and Pearson (2000) divide performance measurement methods into quantitative (based on computation), qualitative (based on assessment) and semi-quantitative (based on ratings that convert judgment into values) methods. They further subdivide quantitative methods into financial method and nonfinancial method. Based on the degree of objectivity or subjectivity of measurement and individuals performing measurement, they classify performance measurement methods in the literature into four following categories: subjective measurement, semi-objective customers' measurement, semi-objective non-involved person measurement, and objective.

There exist some misconceptions that measuring product development productivity may be in contrast with its nature and constraints creativity and demotivates engineers. These misconceptions can be a result of people that fear the measurement of performance will put stress on their inadequacies and lack of productivity or they doubt benefits of such evaluation owing to a previous failure in performance measurement (Brown & Svenson, 1998). In knowledge intensive work like engineering design, demotivation occurs when a performance measurement system is applied inappropriately or it is used simply to control performance without promoting continuous improvement (Parry & Turner, 2006). Resistance to change can also demotivate benchmarking (Comm & Mathaisel, 2000).

Major characteristics of elements of an effective performance measurement system for product development are summarized in the Table 3-1.

Table 3-1 Major characteristics of elements of an effective performance measurement system for product development

Objectives
• Diagnosing activity to support decision making • Motivating personnel • Enhancing communication • Coordination • Learning • Reducing R&D risks and uncertainty • Improving R&D performance (Chiesa, Frattini, Lazzarotti, & Manzini, 2009) Notes: • Objectives of the different functions must be aligned with the overall strategy of the organization. (Neely, Gregory, & Platts, 2005) • The primary objective should be to provide engineers with information to improve their performance. (Parry & Turner, 2006)
Dimensions of performance
• Financial • Market orientation • Efficiency • Innovative capability (Chiesa, Frattini, Lazzarotti, & Manzini, 2009) Notes: • Dimensions must reflect the objectives of measurement and strategies of the organization. • Dimensions must be under control of the evaluated controlled objects. (Neely, Gregory, & Platts, 2005)
Indicators
• Qualitative • Quantitative • Combination of the two (Kerssens-van Drongelen & Cooke, 1997; Tatikonda, 2008; Chiesa, Frattini, Lazzarotti, & Manzini, 2009) • Processing metrics vs. outputs metrics • Financial (monetary-based) vs. non-Financial metrics (Tatikonda, 2008) Notes: • Metrics should be aligned with the strategy of the organization. • Metrics need to be updated over time. • Metrics must be able to measure cross functional process performance. (Parry & Turner, 2006) • Having too many metrics should be avoided. (Kuczmarski, 2001; Parry & Turner, 2006; Bhasin, 2011) • Qualitative metrics should be used in balance with quantitative metrics. (Kerssens-van Drongelen & Cooke, 1997; Chiesa, Frattini, Lazzarotti, & Manzini, 2009) • Different types of metrics should be linked and used in combination. (Kerssens-van Drongelen & Cooke, 1997; Driva, Pawar, & Menon, 2001; Soriano-Meier & Forrester, 2002; Chiesa, Frattini, Lazzarotti, & Manzini, 2009)

Structure
• Individual • Project • R&D unit (Chiesa, Frattini, Lazzarotti, & Manzini, 2009) • Individual • Task • Function (discipline) • Project • Portfolio • Pipeline • Strategic Business Unit (Tatikonda, 2008) Notes: • For each control object, associating performance dimensions and indicators should be defined. (Chiesa, Frattini, Lazzarotti, & Manzini, 2009)
Measurement process
Frequency: • Regular • By milestone (Chiesa, Frattini, Lazzarotti, & Manzini, 2009) Notes: • Performance should be measured regularly. Kuczmarski (2001) **Standards:** • Internal standards • External standards (Kerssens-van Drongelen & Cooke, 1997; Chiesa, Frattini, Lazzarotti, & Manzini, 2009) Notes: • Internal standard can be a performance targets or a past performance. • Performance must also be benchmarked using external standards. • Setting standards is facilitated if a structured project data system is available. (Chiesa, Frattini, Lazzarotti, & Manzini, 2009) • External standards can be industry standards or best practices from market competitors. (Kerssens-van Drongelen & Cooke, 1997)

3.2 Lean performance measurement literature

Lean is no longer considered to be limited to manufacturing processes within the automotive industry in terms of applicability and the benefits it reaps. It is now being adopted successfully within service and new product development processes within different industries (Oppenheim, 2004; McManus, Haggerty, & Murman, 2005; Liker & Morgan, 2006; Baines, Lightfoot, Williams, & Greenough, 2006; Parry & Turner, 2006; Soriano-Meier & Forrester, 2002). Organizations within aerospace sector have also started to implement lean in their product development process (Haque & Moore, 2004). Nonetheless, a performance measurement system that embeds lean principles and has the ability to evaluate efficiency of existing engineering approaches and processes with respect to lean is lacking (Haque & Moore, 2004).

Haque and Moore (2004) conducted a comprehensive research on aerospace companies to develop metrics for evaluation of lean new product development/product introduction processes at enterprise and process level. They first identified existing metrics for measurement of product development/product introduction performance and then chose metrics that supported lean principles. They proposed seven metrics at enterprise level and eight metrics at process level to measure lean performance of new product introduction process in aerospace industry. These measures are represented in the Table 3-2.

Table 3-2 Performance metrics for lean product introduction (Haque & Moore, 2004)

Enterprise Level	Process Level
NPI effectiveness	Speed of design change
Compliance to customer requirements	Number of on-time successful stage gate reviews
Schedule performance	Lead time from agreement of requirements to manufacture
Cost performance	Deviation from target manufacturing cost
Inappropriate design changes	Requirements stability
Information inventory efficiency	Staffing conformance to plan
Engineering throughput	Engineering errors
	Number of warranty claims (or cost of warranties)

Bayou and Korvin (2008) stress that inconsistency in a lean definition and lack of standard leanness measures are two weaknesses of lean manufacturing. In an attempt to deliver a systematic leanness measure, authors first define manufacturing leanness as meeting the objectives of an organization by delivering improved outputs (products and services) while reducing inputs (resources) of the process. They emphasize that to achieve leanness, both efficiency and effectiveness dimensions of the performance should be improved. They assert that leanness is a relative degree and consider leanness as a fuzzy concept in which a company is lean, leaner, or leanest. Figure 3-2 depicts their definition of leanness.

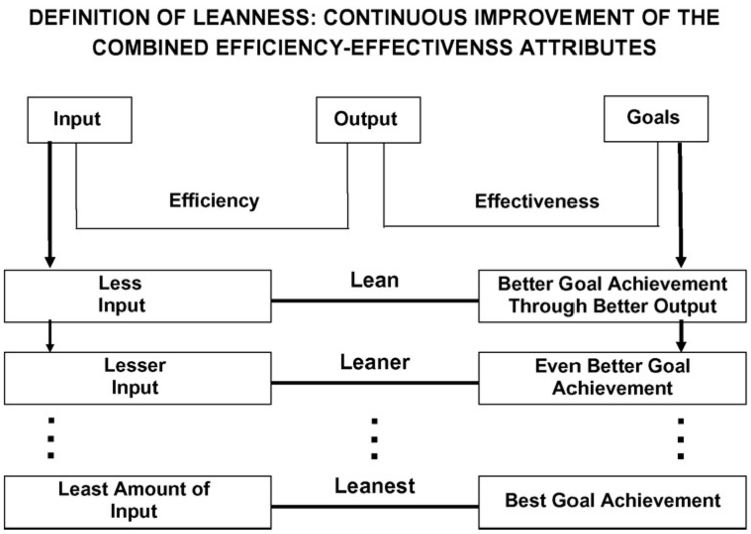


Figure 3-2 Leanness definition (Bayou & Korvin, 2008)

Bayou and Korvin (2008) develop an algorithm to systematically measure the leanness of a production system. The foundation of their leanness measurement process is based on selecting the best performance within the same industry (where performance is measured) as a basis for benchmarking. Next, the performance data regarding a selected set of lean principles is derived from financial statements of the company with the best practice. To measure these principles, they use ‘surrogates’ and evaluate their effects on performance (e.g. they evaluate inventory level to measure Just in Time). The data is used as a performance baseline and fuzzy-logic methodology is utilized to determine the relative level of leanness of the studying company. They apply their measurement method to the automotive industry to compare the leanness of production systems of Ford Motor Company and General Motors using Honda Motor Company as the best practice.

To measure leanness, Bayou and Korvin (2008) take into account only a few lean practices namely: JIT, Kaizen, and quality control, while other lean principles are left out. However, to appropriately measure implementation of lean tools and techniques, all the resulting effects on performance must be identified which requires a comprehensive study and consideration of contextual factors of the work setting. Hence using some surrogates of some lean principles is not enough for proper measurement of lean initiatives. Another shortcoming of such a paradigm is that by the time the data is available for measurement, it is already too late to take corrective actions and data is not actionable.

In a study to develop a model to evaluate the adoption of lean production principles in manufacturing firms (degree of leanness), Soriano-Meier and Forrester (2002) conducted a survey on 33 companies within UK ceramics tableware industry. They first derived nine components of leanness based on the framework developed by Karlsson & Åhlström as follows: the elimination of waste, continuous improvement, zero defects, JIT deliveries, pull of materials, multifunctional teams, decentralization, integration of functions, and vertical information systems. Then they created questionnaires to evaluate the level of lean implementation and the level of commitment of management to lean production. Senior production managers and managing directors of the engaging companies were asked to assess the adoption level of nine lean components in their companies on a seven point scale (ranging from 1 representing no adoption to 7 for total adoption, with 4 for partial adoption). These rates were used in a quantitative analysis to evaluate the degree of leanness of the companies.

Comm and Mathaisel (2000) emphasize on the importance of benchmarking in the lean transformation process. They stress that since leanness is a relative measure, only internal and external benchmarking of performance can enable evaluation of degree of leanness. They argue an effective benchmarking is not limited to evaluation of financial metrics, but it goes beyond to measure performance in terms of time, cost, schedule, and quality. Only this type of benchmarking can enable quality improvement and learning throughout the organization. Companies can learn from each other and implement this learning to improve their performance. Nonetheless, performance dimensions and indicators used should drive lean philosophy. They propose measuring six performance dimensions namely: efficiency, quality, reliability/dependability, capacity, flexibility, and customer satisfaction and list some related indicators for each dimension. They explain an eight step model for evaluation of lean implementation and benchmarking in public sector that at the time was being used in the military aerospace sector. Their proposed model resembles the procedure of DMAIC method with a focus on directing improvements towards a lean manufacturing environment.

Oppenheim (2004) suggested success metrics such as the amount of throughput time cut, amount of waste removed, value stream schedule completed as expected, and good morale of the team to measure lean performance in his lean product development flow framework.

A number of publications focused on examining existing R&D performance measures in literature and practice. Mascarenhas Hornos da Costa, Oehmen, Rebentisch, and Nightingale (2014) conducted systematic literature review, focus-group discussions, and survey to examine most commonly used metrics by program managers during product development management from a lean perspective. They argued that existing categorization methods of metrics proposed in literature do not completely reflect lean principles. Based on the type of information that metrics address, they classified performance measures into new categories namely: stakeholder value and benefits, program objectives and requirements, results from product, results from process, and people. Performance metrics were further discriminated using criteria such as number of metrics per category, unit of analysis, provided level of insight, lean principle fitness, and number of times a metrics was mentioned in literature. They qualitatively evaluated metrics using a survey based on their usefulness and their usage during R&D program management and reported a list of the most and least used and useful metrics. Five most used metrics listed are: 1) certified process, 2) program/project met revenue goals, 3) % growth in sales from new products, 4) labor relations climate between R&D personnel, and 5) exploitation of relationships with partners. They report top five least used metric as: 1) total cost of project, 2) delivery of product to cost, 3) customer satisfaction, 4) new product quality level, and 5) % of respected milestones.

Driva, Pawar, and Menon (2000) conducted a survey to identify product development performance metrics that was used in companies and also identify the metrics that companies intend to implement in the future to measure product development performance. They report total cost of project, on-time delivery of development project, actual project cost compared to budget, actual vs. target time for project completion, and lead time to market as the top five product development metrics used by the companies.

In 1998, Goldense Group, Inc. (GGI) in USA (Teresko, 2008) conducted a survey to find most frequently used R&D metrics within different industries. The top 10 R&D metrics found in their primary research are listed in the Table 3-3.

Table 3-3 Top 10 R&D metrics used by Industry in 1998 (Teresko, 2008)

1) R&D spending as a percentage of sales	76%
2) New products completed/released	68%
3) Number of approved projects ongoing	61%
4) Total active products supported	54%
5) Total patents filed/pending/awarded	51%
6) Current-year percentage of sales due to new products released in past x years	48%
7) Percentage of resources/investment dedicated	46%
8) Percentage of increase/decrease in R&D head count	43%
9) Percentage of resources/investment dedicated to sustaining products	39%
10) Average development cost per projects/product	39%

They conducted the same survey 10 years after in 2008 and reported top 10 most used R&D metrics (see Table 3-4).

Table 3-4 Top 10 R&D metrics used by Industry in 2008 (Teresko, 2008)

1) R&D spending as a percentage of sales	77%
2) Total patents filed/pending/awarded/rejected	61%
3) Total R&D headcount	59%
4) Current-year percentage sales due to new products released in past x years	56%
5) Number of new products released	53%
6) Number of products/projects in active development	47%
7) Percentage resources/investment dedicated to new product development	41%
8) Number of products in defined/planning/estimation stages	35%
9) Average project ROI - return on investment or average projects payback	31%
10) Percentage increase/decrease in R&D headcount	31%

According to Bradford Goldense, GGI's president (Teresko, 2008), an analysis of 86 metrics identified in their 2008 study reveals that although there is no significant change in the top 10 most frequently used metrics, a positive change is occurring in R&D metrics used in practice. They revealed seven major changes as follows: 1) a lot of companies are using the same metrics which will facilitate R&D benchmarking, 2) there is an increase in measuring R&D revenues (use of ‘current-year sales due to products released in the prior x years’ metric increased from 48% to 55%), 3) unlike their 1998 findings, a lot of companies are now measuring R&D

profitability (28% of companies use ‘current year profits due to products released in the prior x years’ metric), 4) there is an overall increase in metrics that measure R&D revenue and profit (e.g. ‘average of returns from projects for first x years’, and ‘revenues and profits after release to market’), 5) due to the emergence of open innovation in the industry use of metrics that can measure multi-party development are increased (e.g. ‘percentage revenues and/or profits from technology licensing’ and ‘percentage revenues and/or profits from technology sales’), 6) there is an increase in measuring productivity of R&D (e.g. ‘products released per engineer or developer’ and ‘revenues and/or profits per engineer or developer’), and 7) companies are improving existing measurement methods and new measures are being developed and implemented (e.g. 20% of companies evaluate 'return on innovation').

The Goldense Group, Inc. (GGI) report (Teresko, 2008) reveals that financial metrics that measure R&D function in term of its share in business profit are on the rise. Yet, as it was mentioned earlier, it is difficult to separate the profit that is resulted by R&D function from the profit resulted from other functions of the organization. These types of financial metrics have their own shortcomings. First, they cannot omit profit share of other functions, therefore the evaluation is not accurate. Second, it is assumed that profitability at a given point in time is the only metric of business performance. To turn a successful design into a successful and profitable product in the market, integrated effort of R&D function along with other function (e.g. marketing and manufacturing) of an organization is required (Chiesa & Masella, 1996).

In the design process of a performance measurement system, contextual factors such as strategy, type, resources, and sector of the target organization should be taken into consideration (Chiesa, Frattini, Lazzarotti, & Manzini, 2009).

Costa, et al. (2014) argue that to ensure successful implementation of lean enablers introduced by Oehmen et al. (Oehmen, et al., 2012) in engineering programs, performance indicators should be used. They propose two types of performance metrics to evaluate the implementation level and the effect of 43 lean enablers on performance.

Beisheim and Stotz (2013) argue that defining key performance indicators for engineering department is a daunting challenge. They claim measuring efficiency of engineering work is not possible by using data provided by existing metrics such as project costs, milestone dates, number of new products, and number of change requests. The authors use already existing product data of purchasing, logistics, engineering, and production departments (derived from product data management (PDM) and enterprise resource planning (ERP) systems) to develop a new KPI for the design and engineering department called standardization degree. According to this metric, each part is categorized into one of the following three categories, namely preferred part, service part, or run-out part, depending on their usage and consumption in a given period of time. They argue that use of this KPI in the beginning of the product development process will lead to reduced product development cost and time. They attempt to promote the idea of reducing the number of parts used in a product by highlighting those parts in preferred part category to the designing team so they could select parts from this category to implement in the final product while developing new products in the future projects.

Chiesa and Masella (1996) argue that every performance measurement system of R&D should have quantitative metrics that evaluate the activities under full or partial control of R&D executives. They present a performance measurement system framework for R&D function and focus on productivity and adherence to scheduling dimensions to evaluate efficiency of R&D. For performance measurement of individual projects, they recommended metrics including the ratio of technical progress to time, the ratio of time to technical progress, the ratio of cost to technical progress, and the ratio of cost to time and to time per technical progress unit. They propose the following metrics for performance measurement of a portfolio of projects: the number of applications generated from single project or sequence of projects, the number of project parts jointly carried out with other projects, the number of duplications, percentage of projects technically successful, and percentage of projects abandoned after a certain degree of completion.

Disregarding non-financial measures and simply relying on financial metrics to measure adoption of lean initiatives significantly reduces the effectivity of measurement. Fullerton and Wempe (2009) stress that methodological inconsistencies, piecemeal adoption of lean elements, and contextual factors can lead to fluctuations in lean manufacturing performance effects. The authors propose another source for lean performance variations i.e. the utilization of non-financial manufacturing performance (NFMP) measures that drive lean practice. They use structural equation modeling (SEM) and collect data using questionnaires from 121 US manufacturing executives to examine the relationship between the utilization of non-financial manufacturing performance measures in the implementation of lean initiatives and the financial performance of a firm.

Fullerton and Wempe (2009) chose the following metrics as non-financial manufacturing performance measures in their study: inventory turns, equipment downtime, on-time delivery, scrap, rework, setup times, labor productivity, throughput time, and manufacturing cycle efficiency. They examine the following relationships: 1) they examine the relationship between shop-floor employee involvement and three lean practices in particular setup time reduction, cellular manufacturing, and quality improvement, 2) they examine the relationship between three lean practices and utilization of NFMP measures, 3) they examine direct relationship between lean practices and financial performance (i.e. profitability), 4) they examine the direct relationship between the utilization of NFMP measures and profitability of a firm, and 5) they examine the mediating role of NFMP measures in the relationship between lean practices and financial performance. Their study reveals that NFMP measurement plays a mediating role and not a moderating role (despite the general belief) in the relationship between lean manufacturing and financial performance of a firm. Thus the utilization of NFMP metrics plays a vital role rather than just an amplifying role in the financial performance of a firm during the lean implementation and transformation process. They stress that data provided by NFMP measurement will enable companies to achieve profitability.

Parry and Turner (2006) report that in addition to performance measurement systems, lean visual tools are also being adopted in organizations to promote and drive lean in real time. They claim that lean visual tools can make the flow of work visual, establish a clear communication throughout the organization, facilitate performance measurement and forecasting, and provide timely feedback, which makes them a dynamic measurement system. Due to their successful implementation in the manufacturing, utilization of these tools is now extended from shop floor to the entire organization. Visual tools such as value stream maps, 5S, Andon boards, updated standard work charts, displays with key financial measures, and Kanban are implemented in a process to demonstrate current state, reveal deficiencies and waste, and to promote continuous improvement to achieve a better future state.

Parry and Turner (2006) argue that use of physical visual tools (a board or a paper) is more effective than using software based tools since due to physical limitation of physical tools only valuable data is represented on such tools while software based tools have no such limitation and are prone to representation of excessive data with no use which can lead to confusion and less effectivity. They reveal that aerospace companies in particular Rolls Royce Civil Aerospace, Airbus UK, and Weston Aerospace have developed lean visual tools in order to promote lean and facilitate communication and performance measurement. For example, in Rolls Royce Civil Aerospace, they have developed a visual control system by communicating the output predicted by ERP system to a large board to display movement of the product through the processes on the shop floor to create smooth flow and support lean manufacturing. In Airbus UK, they have developed visual boards to facilitate management of the process of their Long Range Aircraft Maintenance Manuals division which is a complex knowledge-based process and requires clear communication and transfer of data throughout its entire value stream. They state that all these lean visual tools represent the current state of a complex work process in a simple way and are designed and owned by the teams executing the work themselves.

Beauregard, Thomson, and Bhuiyan (2008) developed a model to evaluate the benefits of introducing lean principles in the engineering process of an aerospace company as part of their research on development of a new framework for lean engineering implementation. They proposed five steps for implementing lean engineering. First, the engineering demand is identified. Second, the engineering value stream bottleneck is identified and targeted for improvement. Third, tasks are scheduled concerning bottleneck process limitations. Fourth, processes upstream of bottleneck are synchronized and coordinated to the pace of the bottleneck process. Fifth, value stream performance is measured in order to monitor the progress. They proposed a lean engineering financial model that evaluates significant aspects of engineering work at different phases during its lifecycle and compares them to a performance baseline.

Beauregard, Thomson, and Bhuiyan (2008) introduced new variables to measure unaccounted for, wasteful aspects of engineering work. For example a variable called restart is proposed that evaluates the amount of time an engineer spends on reviewing an engineering task to be able to continue to progress it after having a long period of inactivity on the task. They also introduced a new variable called wasted setup. In their proposed model, lead time days of each engineering task are classified as either a touch day or a non-touch day based on whether or not a minimum amount of effort (2 hours of work) is spent on the task on that day to advance it. All efforts spent on tasks on a non-touch day (lead time day with charges of less than 2 hours to the task) is then considered waste and are categorized as wasted setup since these effort did not properly advance the task and only wasted resources working on those tasks. Waste is then calculated as the aggregated value of setup, restart, and wasted setup times. Intellectual work in progress (inventory) is equal to the amount of time spent on tasks that remain incomplete at the end of the period of measurement. Then, values of these variables for the period of measurement are converted into financial values by using an hourly engineering rate and are compared to baseline values of the same variables. Engineering performance to fulfill waste reduction, inventory reduction, lead time reduction, and throughput improvement is measured and aggregated to calculate a scalar called lean savings which represents the financial value of all savings achieved due to lean engineering efforts during the period of measurement. Beauregard (2010) used the model to compare performance of pre-certification and post-certification engineering tasks in an aerospace company.

3.3 Lean performance measurement gaps

Research on performance measurement in new product development is very limited relatively (Driva, Pawar, & Menon, 2000; Tatikonda, 2008; Beisheim & Stotz, 2013). Scholars have criticized traditional metrics and performance measurement systems in R&D (Mascarenhas Hornos da Costa, Oehmen, Rebentisch, & Nightingale, 2014). In modern economy, traditional management accounting systems can no longer provide essential data for effective decision making, as they were designed to suit traditional mass production environment. To successfully achieve strategies in long term, it is critical to provide proper feedback at the right time to people who are working to achieve these strategies (Fullerton & Wempe, 2009).

Advanced concepts such as lean are now adopted by organizations to ensure market survival and profitability of the business, however, performance measurement systems that are in place are obsolete and outdated. These performance measurement systems should be reviewed and the metrics need to be modified and updated to correspond to modern product development process needs (Kerssens-van Drongelen & Cooke, 1997; Driva, Pawar, & Menon, 2000; Driva, Pawar, & Menon, 2001; Haque & Moore, 2004). “If lean is the aim, then it is necessary to use performance measures that promote lean behavior” (Haque & Moore, 2004).

Most of the academic research done on product development performance measurement is concentrated on the development of metrics and/or key performance indicators (KPIs) rather than a holistic development of a set of metrics that have proper linkages and could fit in a system of performance measurement for an environment such as product development (Tatikonda, 2008; Kerssens-van Drongelen & Cooke, 1997; Driva, Pawar, & Menon, 2000). Research on how to design this system of performance measurement for different types of research and development activities also requires further attention (Chiesa, Frattini, Lazzarotti, & Manzini, 2009).

Bhasin (2011) summarize the literature on the weakness of traditional performance measures and reports the following shortcoming for traditional measures: traditional measures do not fit strategic decision, traditional metrics are historical and difficult to correlate, they provide little information on the root problems, financial and non-financial measures are weakly connected, traditional measures focus on functional processes (vs cross-functional processes), intangible assets receive small attention, creating value is neglected, too many metrics are used, traditional measures do not promote continuous improvement, and operational and strategic level measures are not effective connected.

Tatikonda (2008) stress that most recent studies on new product development performance measurement focus on project level tactical outcomes and SBU level financial and market outcomes while there is a gap on measurement of objects at the intermediate organizational level, linking metrics, developing metrics as a set, and developing effective predictive processing measures (versus existing historical outputs metrics).

Most of the studies reviewed in the previous section focused on identifying some metrics (that are used in the industry) and/or developing some individual measures to promote lean while others developed qualitative measures of leanness.

A number of proposed metrics count the number of failures and/or successes in the engineering process. On the one hand, there are metrics that try to count the number of failures (errors) in engineering work. For example, a metric like the number of design changes only indicates how many times a change has occurred to a design in the product development process (pre or post release to manufacturing) without elaborating on how these changes affected the process in terms of time, cost, and effort (how much effort was spent to implement changes, correct the designs and how much waste was produced).

Changes to design can be a result of a request from a customer, a change in specifications, or due to an engineering error (Haque & Moore, 2004). Each design change has different impact (magnitude) on the product development process. Factors such as the dimension in which the change occurs, when it occurs (early or late in the process), and the magnitude of the dependencies of other designs (how sensitive designs are to this change) to this change can affect the impact of a design change. A change in a specification that can make all the downstream effort useless which requires a complete redesign of all dependent elements in the system is different than a small change in a parameter that will only result in minor rework (Design Structure Matrix is one of the tools used to define relationships and dependencies of design elements). Design changes made earlier in the process of product development are less costly and easier to correct. As we move forward in the product development process these changes impose more cost and effort e.g. changes made after release of design to production (McManus, Haggerty, & Murman, 2005). Therefore, we need metrics that can appropriately discriminate the performance of product development process not only based on the number of changes occurred but also considering the effect of these changes (the magnitude) so we could accurately benchmark performance.

On the other hand, there are metrics that try to count the number of success (achievements) in the product development process. For example metrics such as the number of new designs introduced. This type of metrics that only count the outcomes of a complex engineering effort neglect one important aspect that is the level of efficiency with which the engineering process delivered those outcomes. It may happen that an engineering department delivers more new designs in a period but with a greater percentage of waste occurred during that period. Thus, such metrics does not reflect the level of efficiency of the engineering department and simple use of them will falsely imply that a better performance was achieved in a period leaving out the efficiency. Another problem associated with this type of bibliometric analysis is that a greater value for such metrics does not necessarily lead to a better business performance, hence, these metrics are only helpful when they are analyzed along with other type of metrics in a comprehensive performance measurement system (Kerssens-van Drongelen & Cooke, 1997).

A number of researchers developed qualitative measures of leanness. They based their evaluation of leanness on questionnaires and only considered implementation of some lean components, disregarding lean as a system of principles. For example, evaluation of the degree of leanness based on a questionnaire as conducted by Soriano-Meier and Forrester (2002) has its own drawbacks. First, as any other qualitative assessment method, subjectivity and bias can highly affect the results. Second, a higher level of commitment to lean and adoption of its components and techniques does not necessarily lead to a higher degree of leanness.

It is neither how much you want to become lean, nor how many lean tools you use that define leanness. Lean tools are implemented in a process so that a lean state of performance can be achieved, hence, the outcome of such implementation (effectivity and efficiency of the performance) is the appropriate metric for evaluation of the degree of leanness. Rather than assessing the rate of lean components adoption, achieved performance must be evaluated with respect to lean goals. In their research, they viewed lean as a set of elements rather than a system of principles. These lean elements are all designed to serve as a springboard for building a lean process. There is no lean implementation approach that fits all companies (Bhasin, 2011). One should appropriately select the techniques that fit and are effective for a given work environment. Appropriate systematic application of lean principles is required to ensure leanness and the degree achieved can only be evaluated based on the objective measurement of outcomes of the application process and not based on the subjective assessments of the inputs of the process.

Performance measurement models that are capable of evaluating the degree of leanness in organizations are missing, hence, objective comparison and benchmarking of leanness is a challenge (Soriano-Meier & Forrester, 2002; Bayou & Korvin, 2008). Implementation of a common model that integrates key lean performance indicators eliminates measurement inconsistencies and enables relative and reliable benchmarking that can identify best practice and drive continuous improvement by implementing best practice throughout the organization. Utilization of a common performance measurement system will promote continuous improvement, competitiveness, and enables internal and external benchmarking throughout the organization and across industries (Haque & Moore, 2004; Bayou & Korvin, 2008).

Following, a number of weaknesses associated with research on lean product development performance measurement is summarized: 1) focus on developing individual measures rather than developing a set of properly linked metrics (Kerssens-van Drongelen & Cooke, 1997; Driva, Pawar, & Menon, 2000; Tatikonda, 2008; Bhasin, 2011), 2) formulate lean as implementation of some tools and not a system of principles while measuring leanness of an organization, 3) efficiency of engineering process which is the third goal of lean engineering (McManus, Haggerty, & Murman, 2005) is left out, 4) provide little information that is historical and not actionable (Tatikonda, 2008; Bhasin, 2011); by the time the feedback is available it is too late to make any corrective or predictive action, 5) have too many metrics (Kuczmarski, 2001;

Bhasin, 2011), 6) do not promote lean behavior (Bhasin, 2011), 7) do not provide engineers with useful information to help improve their performance, 8) do not account for wasteful aspect of engineering work; since waste parameters are often transferred from manufacturing process disregarding wasteful aspects of work that only exist in engineering (e.g. the time required for mental preparation of engineers that changes in time in the case of idleness), and 9) leanness is qualitatively evaluated based on questionnaires (subjective vs objective measurement of the level of leanness) which can highly be subject to personal preference and bias (Kerssens-van Drongelen & Cooke, 1997; Tatikonda, 2008; Chiesa, Frattini, Lazzarotti, & Manzini, 2009).

4 LEAN ENGINEERING PERFORMANCE MEASUREMENT MODEL

In this chapter, the lean engineering performance measurement (LEPM) model developed in this research is presented and discussed in detail.

4.1 LEPM model: Introduction

To address the need for a performance measurement model (vs. an individual lean metric) that takes into account key lean principles and performance indicators, a lean engineering performance measurement (LEPM) model is developed. The model comprises a set of metrics to evaluate the efficiency of engineering processes from a lean perspective. In the development of the model, lean is treated as a system of principles rather than implementation of some tools, hence, a set of metrics is developed that is capable of evaluating the effects of implementing lean initiatives in the overall performance of an engineering process. The LEPM model can help managers with choosing the right set of available lean tools and techniques in the process of lean transformation by providing them with information that is vital for effective decision-making. Therefore, best practices can be identified and extended to the whole organization, thus, more improvements can take place.

The LEPM model is used on a periodic basis to measure key performance dimensions of engineering tasks from a lean perspective. Measured values are then compared against some previously established baseline that is used as a standard to determine the progress achieved towards lean goals of waste elimination, lead time reduction, intellectual inventory reduction, and throughput improvement. The focus of the model is on evaluating the efficiency of engineering processes, the third goal of lean engineering as stated by McManus, Haggerty, and Murman (2005).

The LEPM model provides a number of benefits in an engineering process: it provides a unified system to collect, measure, analyze, and report lean performance of an engineering process; it allows benchmarking of engineering performance at different levels (e.g. individual, team, product family level); it provides visibility to and quantifies engineering waste; enables measuring performance effects of alternative lean tools and techniques in order to identify the best practice; it enables setting targets for performance and promotes lean engineering and continuous improvement; and it facilitates organizational learning and decision-making by the providing vital data on performance

4.2 LEPM model: Measurement process overview

In a lean engineering transformation process, after defining the value and mapping the value streams, while the transition from the current state to a planned future state starts, the LEPM model can be run on a periodic basis (e.g. monthly). This can help to evaluate performance towards achievement of a lean engineering process by providing a clear understanding of how the company is doing with respect to fulfillment of the goals of a lean engineering process. Figure 4-1 depicts major inputs and outputs of LEPM model.

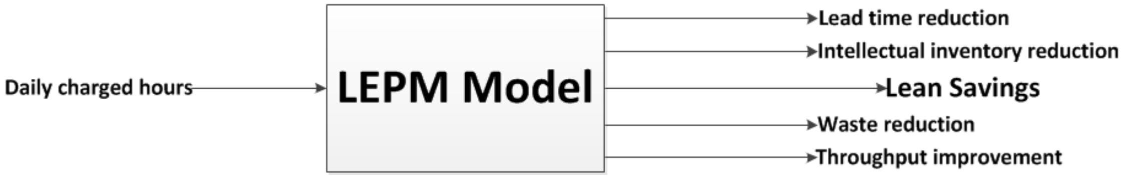
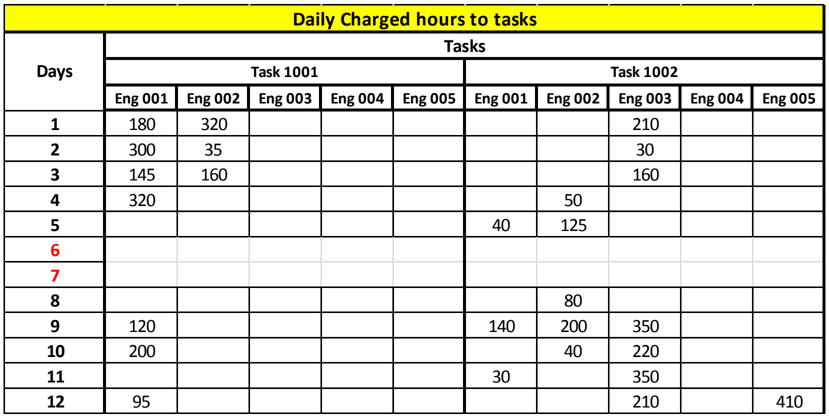


Figure 4-1 Major inputs and outputs of LEPM model

The measurement process starts by classification of value stream tasks based on their status in the system at the time of measurement. To measure performance, the daily amount of time spent on each value stream task by each engineer during the period of measurement is required. Data can be collected via excel sheets, done by engineers executing the tasks, or be extracted from time cards, or any other available systems in the organization that collects such data (e.g. SAP software). A sample of an excel sheet used for data collection is shown in Figure 4-2.



Daily Charged hours to tasks										
Days	Tasks									
	Task 1001					Task 1002				
	Eng 001	Eng 002	Eng 003	Eng 004	Eng 005	Eng 001	Eng 002	Eng 003	Eng 004	Eng 005
1	180	320						210		
2	300	35						30		
3	145	160						160		
4	320						50			
5						40	125			
6										
7										
8							80			
9	120					140	200	350		
10	200						40	220		
11						30		350		
12	95							210		410

Figure 4-2 Daily charges to tasks by engineers collected via excel sheets

Next, available value stream hours and time spent on tasks are decomposed into value-added (VA), non-value-added (NVA), and required non-value-added (RNVA) parameters. Based on these values, the amount of waste and throughput is evaluated. Next, using a previously established baseline, measured values are benchmarked and the values of lead time reduction, intellectual inventory reduction, Waste reduction, and throughput improvement is calculated for the period of measurement. Finally, the total value of lean savings during the measurement period is evaluated.

4.3 LEPM model: Description and formulation

The first step of performance measurement is to determine the status of each value stream task in the product development system and classify it into one of the following three categories:

1) Completed tasks ($|\mathrm{I}| = \mathrm{n}$): tasks that are completed (delivered) during measurement period.

$\mathrm{i} \in \mathrm{I} = 1, .., \mathrm{n}$: Completed tasks

2) Active incomplete tasks ($|\mathrm{I}'| = \mathrm{n}'$): active tasks in the system that are not completed during measurement period.

$\mathrm{i}' \in \mathrm{I}' = 1, .., \mathrm{n}'$: Active incomplete tasks

3) Non-active incomplete tasks ($|\mathrm{I}''| = \mathrm{n}''$): tasks that are suspended (aborted) before being completed or completed tasks that are not incorporated into the final product (e.g. developed features that are dropped).

$\mathrm{i}'' \in \mathrm{I}'' = 1, .., \mathrm{n}''$: Non-active Incomplete tasks

Then, the available working time for the value stream (total working time available for resources to work on values stream tasks during the period of measurement) is decomposed into smaller elements which can be further classified as VA, NVA, and RNVA effort. We need to break down value-added activities in order to enable visibility of hidden non-value-added activities, since most of these wasteful efforts exist within larger value-added activities (Oppenheim, 2004).

Without such decomposition, measuring performance of engineering activities from a lean perspective would not be effective as a significant amount of engineering waste is left out and is considered to be an inherent part of the normal effort required to process a task (existing studies lack such a decomposition). Therefore, the following flowchart (Figure 4-3) is developed to help break down available value stream working hours into proposed LEPM model parameters. These parameters make the hidden non-value-added part of engineering activities transparent so one could appropriately measure the effectiveness and efficiency with which the available working hours was used to progress the tasks towards completion.

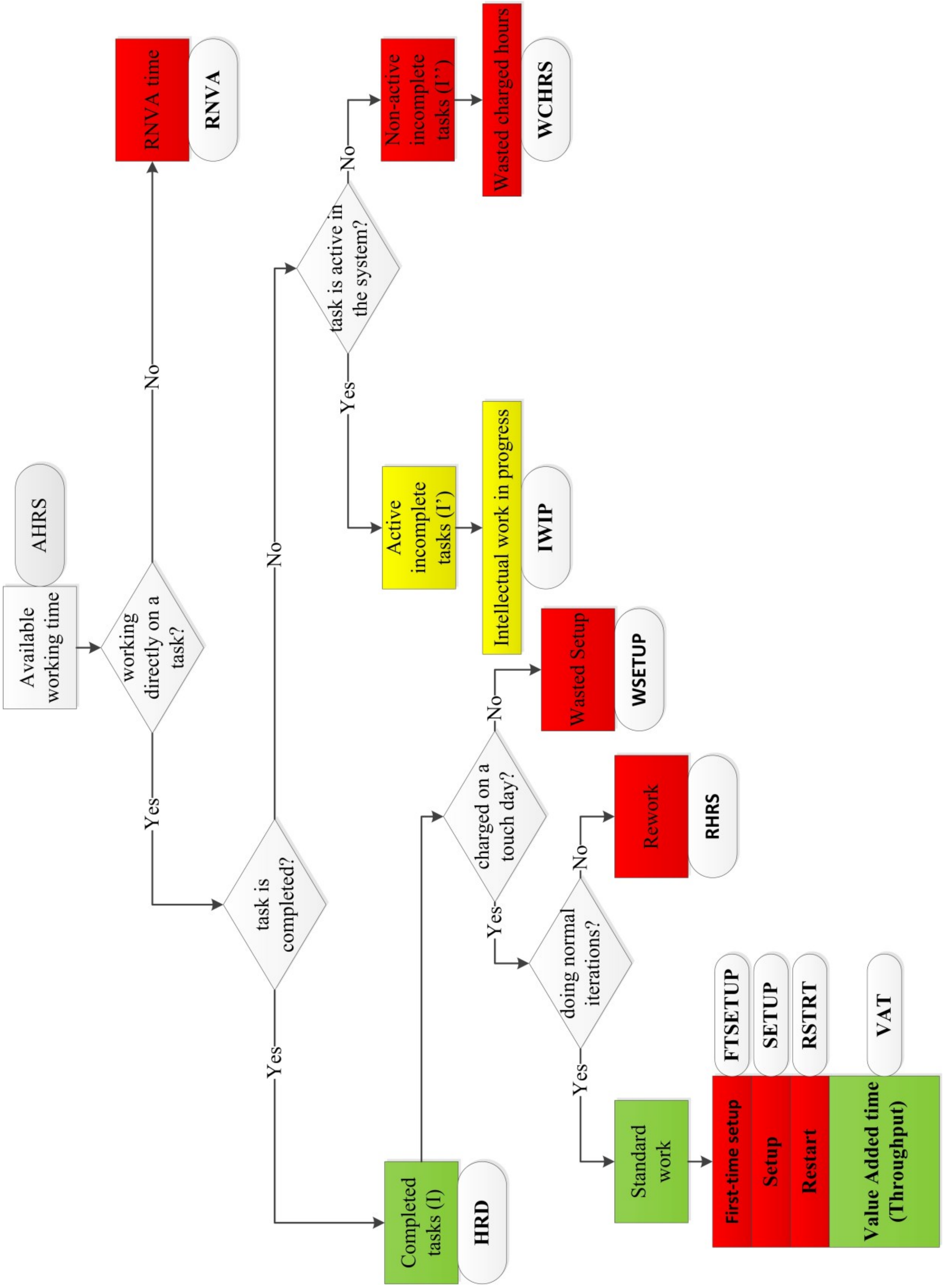


Figure 4-3 Available working time decomposition in LEPM model

The decomposition process is discussed in detail in this section.

For each completed task (i), lead time (LT_i) is calculated as the number of elapsed days between the first charge and the last charge to that task minus the number of non-working days within this period.

$$LT_i = F_i - S_i - NWD + 1 \tag{1}$$

where F_i is the date of last hour charged to task i, S_i is the date of first hour charged to task i, and NWD is the number of non-working days (e.g. weekends, holidays) within the lead time period.

Average task lead time ($\overline{LT}$) is evaluated:

$$\overline{LT} = \frac{\sum_{i=1}^{n} LT_i}{n} \tag{2}$$

where n is the number of completed tasks during the measurement period.

Average charged hours ($\overline{CHRS}$), is the total amount of time charged to completed tasks over the number of completed tasks.

$$\overline{CHRS} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} CHRS_{ijk}}{n} \tag{3}$$

where $i \in I = 1,..,n$ is the number of completed tasks, $j \in J = 1,..,m$ represents the number of working days within period of measurement, $k \in K = 1,..,l$ represents the number of engineers (resources) in the engineering system, and $CHRS_{ijk}$ is the hours charged to task i on day j by engineer k.

The average number of engineers ($\overline{N}$) that charged to completed tasks is calculated as follows:

$$\overline{N} = \frac{\sum_{i=1}^{n} N_i}{n} \tag{4}$$

where N_i is the number of engineers that charged to task i.

Hours delivered (HRD) is simply the total amount of hours charged to completed tasks.

$$HRD = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{l} CHRS_{ijk} = n \times \overline{CHRS} \tag{5}$$

As previously discussed, in addition to the non-value-added part of engineering effort, idleness of tasks also significantly contributes to the creation of waste in the engineering process. One study shows only 31% of engineering effort is value-added while engineering work packages are idle in the system 62% of the time (McManus, Haggerty, & Murman, 2005), hence, only 12% of the time a task undergoes value-added activity (McManus, 2005). Idleness of tasks also leads to an increased level of work in progress inventory which is another major source of waste. More importantly, this intellectual work in progress inventory contains valuable information that can lose its value in time.

Technologies become obsolete, engineering errors remain hidden, and even projects can fail if this information is stored without being worked on for a long time. Kato (2005) defines rotten inventory as the information inventory that requires partial or complete rework due to internal or external changes caused by market change, requirements change, and technical difficulties. He reports in one case study, the information stored as inventory was wasted at the rate of 6% a month, meaning that a task that is idle for a month on average requires an extra 6% of effort by engineers in order to be delivered. This puts more emphasis on the importance of minimizing inventories in the product development system, as holding larger inventories of information leads to more rework and higher levels of inventory, since the engineers need to stop other tasks and charge extra effort to these tasks in order to deliver them. On the other hand, the more and longer the tasks are idle in the system before being worked on again, the more and longer mental setup is required by engineers to complete them (Bauch, 2004). Hence, idleness of tasks creates a chain of wasteful events in the engineering value stream leading to poor performance. Therefore, by reducing idleness of tasks, the waste is reduced and engineering performance is improved.

In what follows, a number of metrics are discussed that highlight and account for such type of waste and promote incremental improvement in those dimensions.

Each lead time day of a given task is classified as either a touch day or alternatively a non-touch day, based on whether or not charges made to the task on that day effectively contributed to the progression of the task. A predetermined parameter called $MTTP_i$, that is the minimum time required to effectively progress task i, is used for such classification. The value of $MTTP_i$ for each task or product family depends on the contextual factors and is determined inside the company based on previous performance data and discussion within engineering teams executing the tasks. Each lead time day is then considered a touch day if a minimum of $MTTP_i$ hours is spent on the given task during that day by at least one engineer. Setup time (intellectual, paperwork or computer), and task complexity are among factors that set a minimum limit to the time that is required to effectively progress a task. A task with greater setup time and/or greater complexity will consequently require a greater amount of time to be effectively progressed, therefore, has a greater $MTTP_i$ value. If the amount of time spent on a task by engineers during a lead time day is lower than $MTTP_i$, then charges on that day do not effectively contribute to progression of the task towards completion and that day is classified a non-touch day. The average number of touch days $\overline{TD}$ is calculated using the formula below:

$$\overline{TD} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} TD_{ij}}{n} \tag{6}$$

TD_{ij} is a binary variable indicating whether day j for task i is a touch day or alternatively a non-touch day. For each task (i) we have $TD_{ij} = 1$ if $CHRS_{ijk} \geq MTTP_i$ for at least one engineer k on day j, otherwise $TD_{ij} = 0$.

$$\overline{NTD} = \overline{LT} - \overline{TD} \tag{7}$$

where $\overline{NTD}$ represents the average number of non-touch days.

Touch time ratio (TTR) is the number of touch days over lead time. It evaluates how effective the lead time is used to progress the tasks towards completion. The lower the touch time ratio, the idler the task has been in the system within its lead time period. This inactivity results in increased level of intellectual work in progress, longer lead times, and longer queues in the engineering system, thus increasing waste and lowering performance. A value stream with a low touch time ratio should immediately be analyzed in order to identify root causes of the problem to increase the touch time ratio.

$$TTR = \frac{\sum_{i=1}^{n} \frac{TD_i}{LT_i}}{n} \tag{8}$$

TTR represents the touch time ratio of completed tasks, and $TD_i = \sum_{j=1}^{m} TD_{ij}$ is the total number of touch days of task i.

The task idleness mentioned earlier is a result of high number of days with no charge and/or days with charges lower than $MTTP_i$. Kato (2005) identifies thirteen types of inventory of information (reasons for which information is stored as inventory and task becomes idle) in product development as follows: 1) taking care of a more urgent task in the project, 2) switching to a higher priority task outside of the project, 3) waiting for information from another task, 4) review/testing work, 5) day off, 6) maintenance of documents, 7) rework discovery, 8) other engineers' availability, 9) downstream engineer's availability, 10) waiting for an answer, 11) ambiguous information, 12) limited availability of tool/board/system, and 13) Others. Charged hours to tasks on non-touch days are considered waste in this model in the sense that these charges do not significantly progress the task towards completion and at the same time interrupt continuous flow of other tasks that engineers could have been charging to instead (Beauregard, Thomson, & Bhuiyan, 2008).

Based on Little's Law we know that the following relationship between work in progress, throughput, and lead time holds for a production system:

$$\mathrm{WIP} = \mathrm{Throughput} \times \mathrm{lead\ time} = \mathrm{T} \times \mathrm{LT} \tag{9}$$

Therefore to reduce work in progress inventory which is waste and requires extra financing, the lead time must be reduced. Lead time reduction can be achieved either by increasing the touch time ratio or decreasing the average task lead time (Beauregard, Thomson, & Bhuiyan, 2008).

Hours charged to active incomplete tasks ($\mathrm{i}' \in \mathrm{I}' = 1, .., \mathrm{n}'$) during the measurement period are considered intellectual work in progress ($IWIP$). Intellectual work in progress is the amount of engineering work waiting in the system to be further processed before it can be delivered. Work in progress is a form of inventory, therefore holding an excess level of it is considered waste since the capital tied up in it could be used elsewhere to generate higher amount of returns for the organization. Reducing intellectual work in progress levels results in increased cash flow (due to faster order to cash cycle) and more profit for all the stakeholders (Beauregard, Thomson, & Bhuiyan, 2008).

$$IWIP = \sum_{i'=1}^{n'} \sum_{j=1}^{m} \sum_{k=1}^{l} CHRS_{i'jk} \tag{10}$$

where $IWIP$ represents the intellectual work in progress hours at the end of the measurement period, $i' \in I' = 1, .., n'$ is the number of active incomplete tasks, and $CHRS_{i'jk}$ is the amount of hours charged to active incomplete task i' on day j by engineer k.

Evaluation of waste starts by calculating the amount of wasted charged hours. The total amount of time spent on non-active incomplete tasks such as incomplete tasks that are aborted, or completed tasks that are not incorporated into the final product (e.g. developed features that are dropped) is classified as wasted charged hours ($WCHRS$), owing to the fact that effort spent on these tasks did not create any value for stakeholders and the time could have been used to progress a value-added tasks instead.

$$WCHRS = \sum_{i''=1}^{n''} \sum_{j=1}^{m} \sum_{k=1}^{l} CHRS_{i''jk} \tag{11}$$

where $WCHRS$ represents the wasted charged hours, $i'' \in I'' = 1, .., n''$ is the number of non-active incomplete tasks, and $CHRS_{i''jk}$ is the hours charged to task i'' on day j by engineer k.

Developed knowledge for tasks that are classified under this category needs to be properly documented and shared across the engineering teams so that learning can occur (engineer can learn from mistakes and prevent reinvention of knowledge). If knowledge is effectively captured, individual learning will lead to organizational learning (Lander & Liker, 2007). One of the barriers to sharing information of such failed tasks is the existence of a blame culture in organizations. Instead of blaming engineers, the root cause of the failure must be analyzed and targeted (Oehmen, et al., 2012). Knowledge developed for such activities may also have the potential of being used in another project.

One of the lean techniques used in engineering companies is set-based design. In set-based design, multiple alternative designs are taken into account and developed simultaneously and decisions are delayed as much as possible in the process to keep the design space open. The number of design alternatives needs to be kept limited otherwise this process becomes a resource of waste itself. These companies will surely end up with some designs that are not implemented into the final product (Haque & Moore, 2004). The $WCHRS$ metric enables manager to effectively make decisions on choosing the appropriate level of set based design (vs. point based design) to run future tasks based on performance information that the model provides.

A key aspect in the product development process is the effective capture of customers' subjective statements of requirements for the products and services (voice of the customer). The next step is to effectively convert these requirements into objective characteristics for products and services which appropriately correspond and meet the demands of all stakeholders. Quality function deployment (QFD) is one of the powerful tools widely used in the industry which will streamline this process. This will result in a reduction in the effort spent on development of features and products which does not comply with customers' requirements (reduction in value of the $WCHRS$ metrics) and are a waste of time, cost and resources and affect project schedule and budget.

Before charging to a task for the first time, engineers need to analyze requirements of the task and mentally prepare themselves. This process is time consuming. Depending on the task type, task complexity, and skills and proficiency of the engineers, this preparation may require some minutes to several hours.

$$\overline{FTSETUP} = FTST \times \bar{N} \tag{12}$$

where $\overline{FTSETUP}$ represents average first-time setup time, and $FTST$ is a predetermined value that represents average time required for an engineer to setup for a task for the first time.

Any type of setup is a non-value-added activity and reducing it is an important goal of lean. Single Minute Exchange of Die (SMED) developed by Shigeo Shingo is one of the most well-known methods of setup reduction in lean manufacturing.

In addition to first time setup, each time an engineer charges to a task, or there is a change of tasks occurring, some effort (intellectual, paperwork, or computer) is required to prepare engineer for the task.

$$\overline{SETUP} = \frac{ST \times \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} SETUP_{ijk} \times TD_{ij}}{n} \tag{13}$$

where $\overline{SETUP}$ represents average setup time, ST is a predetermined value that refers to the average time required for an engineer to setup for a task, and $SETUP_{ijk}$ is a binary variable where $SETUP_{ijk} = 1$ if $\mathrm{CHRS}_{\mathrm{ijk}} > 0$, and $SETUP_{ijk} = 0$ otherwise. All charged hours to a task on a non-touch day are considered waste and are later categorized as wasted setup in the model. To prevent recalculation of setups for these charges, $SETUP_{ijk}$ is multiplied by TD_{ij} in the formula above.

For each time an engineer that has more than a predetermined period of inactivity (no charge) on a given task and charges again to the task after this period, another type of setup called restart ($RSTRT$) is determined in the model. This restart is assigned to account for extra preparation and review that is required before charging again to the task and is different from the regular setup mentioned earlier.

$$\overline{RSTRT} = \frac{RT \times \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} RSTRT_{ijk}}{n} \tag{14}$$

where $\overline{RSTRT}$ represents average restart time, RT is a predetermined value referring to the average time required for an engineer to restart for a task, $RSTRT_{ijk}$ is a binary variable where $RSTRT_{ijk} = 1$ if there is a period of more than RP days of inactivity between the charge of engineer k on day j to task i and the last charge of that engineer to the task, and $RSTRT_{ijk} = 0$ otherwise. RP is the predetermined duration of inactivity period that requires the engineer to restart prior to charging to the task again.

As mentioned earlier, all charged hours to tasks on non-touch days are considered waste and are classified as wasted setup.

$$\overline{WSETUP} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} CHRS_{ijk} \times (1 - TD_{ij})}{n} \tag{15}$$

where $\overline{WSETUP}$ represents average wasted setup.

Rework is a major contributor to waste, leading to poor cost and schedule performance. Rework iterations are time and resource consuming. Rework here refers to extra iterations that are performed to correct work (information) already completed. In engineering work, rather by doing non-value-added activities, waste is mostly created by performing value-added activities with the wrong information which imposes a lot of rework on the engineering system (Browning, 2000). Insufficient quality of information, low quality processing, change in requirements, and availability of new information are among factors leading to rework.

$$\overline{RHRS} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} RHRS_{ijk}}{n} \tag{16}$$

where $\overline{RHRS}$ represents average rework, and $RHRS_{ijk}$ is the rework hours (hours spent on a task to correct the work already done) charged to task i on day j by engineer k.

Available working time ($AHRS$) is simply the total amount of hours engineers were available to work on value stream tasks during the measurement period.

$$AHRS = \sum_{j=1}^{m} \sum_{k=1}^{l} AHRS_{jk} \tag{17}$$

where $AHRS$ represents the available working time, and $AHRS_{jk}$ is the available working hours of engineer k on day j.

A significant amount of an engineer's available working time is spent on required non-value-added activities such as creating presentations, reports, updating databases and schedules, or other tasks which are an inappropriate use of an engineer's skills (Bauch, 2004). In aerospace, roughly every engineering task requires a formal process for tractability, quality, safety, and regulatory purposes. These formal processes mostly refer to outdated practices, and include irrelevant data, or lack key practices and lead to inefficiency of engineering processes (McManus, Haggerty, & Murman, 2005). Recent defense contracts also suffer from a significant amount of required non-value-added activities such as ample administrative responsibilities, complex reports, approvals, and releases (Oppenheim, 2004). Time spent on such required non-value-added activities must be minimized and eliminated where possible. RNVA time variable in this model, allows for evaluation of time spent on such activities in order to highlight this wasteful dimension of engineering work and promote minimizing it.

RNVA time reflects the amount of time engineers do not charge directly to activities that progress a value stream task towards completion but they work on necessary supporting tasks e.g. the time spent to review work (inspection), create reports and presentations for a task. The amount of non-productive time can also be classified into this variable (e.g. time that engineers spend waiting for information, approvals, and verifications).

$$RNVA = AHRS - [HRD + IWIP + WCHRS] \tag{18}$$

where $RNVA$ represents the RNVA (required non-value-added time) time. It should be noted that while measuring charged hours to tasks for the period of measurement, the amount of time that is spent on such supporting activities should not be included in the charged hours $(CHRS_{ijk})$ in order to enable calculation of such metric using this equation.

Next, the calculation of waste for the value stream is performed. Average waste for completed tasks is evaluated by aggregating the average values of first-time setup, setup, restart, wasted setup, and rework.

$$\overline{WASTE_I} = \overline{FTSETUP} + \overline{SETUP} + \overline{RSTRT} + \overline{WSETUP} + \overline{RHRS} \tag{19}$$

$\overline{WASTE_I}$ is the average waste for completed tasks.

$$\overline{WPCY_I} = 100 \times \frac{\overline{WASTE_I}}{\overline{CHRS}} \tag{20}$$

$\overline{WPCY_I}$ is the percentage waste for completed tasks.

Average waste for active incomplete tasks is evaluated by calculating the five mentioned waste metrics for active incomplete tasks by replacing set of completed tasks ($i \in I = 1, .., n$) with the set of active incomplete tasks ($i' \in I' = 1, .., n'$) in the equation above and calculating each metric for active incomplete tasks.

$$\overline{WASTE_{I'}} = \overline{FTSETUP_{I'}} + \overline{SETUP_{I'}} + \overline{RSTRT_{I'}} + \overline{WSETUP_{I'}} + \overline{RHRS_{I'}} \tag{21}$$

where $\overline{WASTE_{I'}}$ is the average waste for active incomplete tasks.

$$\overline{WPCY_{I'}} = 100 \times \frac{\overline{WASTE_{I'}}}{\frac{IWIP}{n'}} \tag{22}$$

$\overline{WPCY_{I'}}$ is the percentage waste for active incomplete tasks.

Finally, by adding wasted charged hours and RNVA time to the sum of waste of completed tasks and active incomplete tasks, the total amount of waste ($TWASTE$) in the engineering value stream is evaluated.

$$TWASTE = (n \times \overline{WASTE}_I) + (n' \times \overline{WASTE}_{I'}) + WCHRS + RNVA \tag{23}$$

where $TWASTE$ represents the total waste.

$$\overline{WPCY} = 100 \times \frac{TWASTE}{AHRS} \tag{24}$$

$\overline{WPCY}$ is the percentage total waste.

Year to date throughput hours (T_Y) is the difference between available working hours and total waste.

$$T_Y = AHRS - TWASTE \tag{25}$$

where T_Y refers to the year to date throughput hours.

$$T_D = \frac{T_Y}{m} \tag{26}$$

T_D is the daily throughput, and m is the number of working days within measurement period.

$$TDPRH = \frac{T_Y}{AHRS} \tag{27}$$

where $TDPRH$ represents throughput delivered per resource hour.

Rework rate is calculated as the total amount of rework hours charged to completed tasks over the hours delivered.

$$RR = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} RHRS_{ijk}}{HRD} \tag{28}$$

where RR represents rework rate.

For each completed task, the processing time (PT_i) is evaluated.

$$PT_i = \sum_{j=1}^{m} \sum_{k=1}^{l} CHRS_{ijk} \tag{29}$$

where PT_i represents task processing time.

Value-added time for each task is evaluated by subtracting the amount of waste incurred while performing the task from the processing time of the task.

$$VAT_i = PT_i - [\overline{FTSETUP_i} + \overline{SETUP_i} + \overline{RSTRT_i} + \overline{WSETUP_i} + \overline{RHRS_i}] - RNVA_i \tag{30}$$

where VAT_i represents value-added time of task i.

$$VATP_i = \frac{VAT_i}{PT_i} \tag{31}$$

where $VATP_i$ represents percentage value-added time for task i.

Decomposition of processing time to discriminate value-added effort from non-value-added effort in LEPM model is depicted in the Figure 4-4.

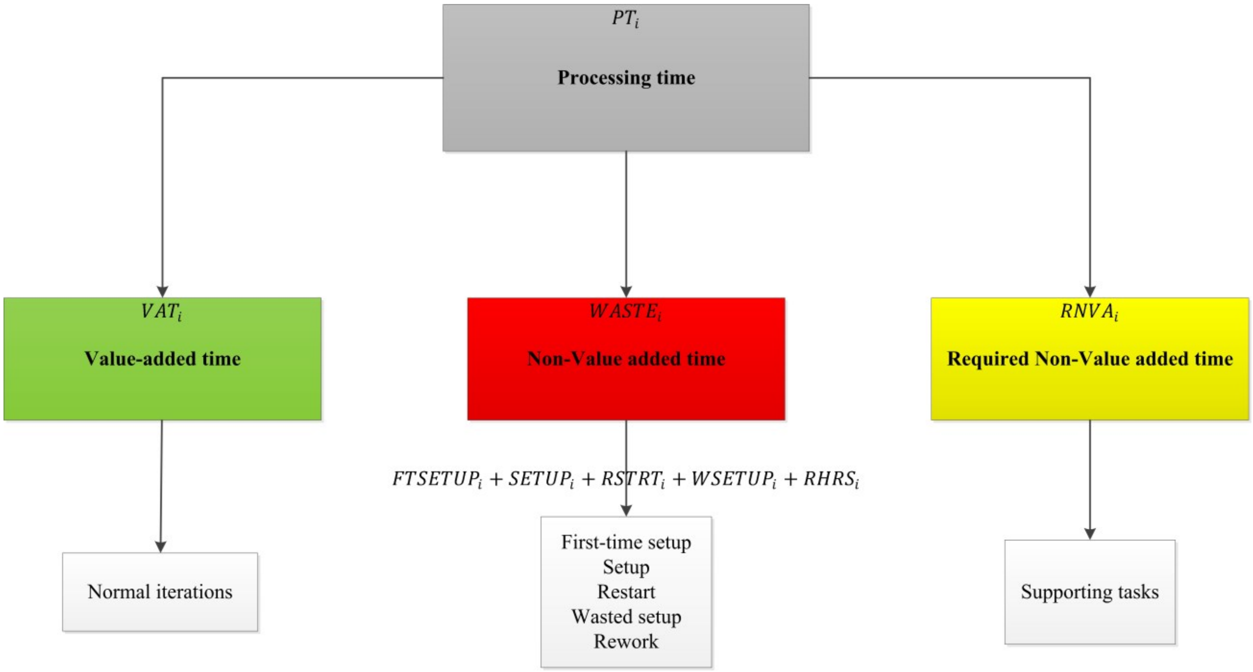


Figure 4-4 Processing time decomposition in LEPM model

Now, the engineering performance during measurement period is compared to a previously established baseline.

$$\overline{WPCI} = \overline{WPCB} - \overline{WPCY} \tag{32}$$

where $\overline{WPCI}$ represents percentage waste improvement, and $\overline{WPCB}$ is the percentage waste baseline that is used as a standard to benchmark performance against.

Year to date throughput improvement (TI) is the difference between year to date throughput hours and prorated baseline throughput hours.

$$TI = T_Y - (T_B \times \frac{M}{12}) \tag{33}$$

where TI represents year to date throughput improvement, T_Y is the year to date throughput hours, T_B is the baseline throughput, and M is the number of months within the period of measurement used to prorate the baseline throughput hours.

Major benefits of lean implementation in the engineering process are lead time reduction, waste reduction, throughput improvement, and intellectual work in progress inventory reduction. These values are calculated using an hourly engineering rate (R) in this model (Beauregard, Thomson, & Bhuiyan, 2008).

Lead time reduction savings can be achieved by a reduction of the number of non-touch days and/or a reduction of the average task lead time as discussed earlier. A reduction in the number of non-touch days will decrease carrying cost for intellectual work in progress inventory $(IWIP)$. Holding tasks in inventory delays generation of potential revenues which can be earned by delivering those tasks. Carrying cost for intellectual work in progress can be calculated using weighted average cost of capital (WACC), or carrying cost (cc) (Beauregard, Thomson, & Bhuiyan, 2008).

$$LTR_{NTD} = \left(\frac{\left(NTD_B \times \frac{M}{12}\right) - NTD_Y}{n + n'}\right) \times \overline{IWIP}_P \times R \times cc \tag{34}$$

where LTR_{NTD} represents saving associated with a reduction in the number of non-touch days, NTD_B is the baseline non-touch days, NTD_Y is the year to date non-touch days (total number of non-touch days for all complete and active incomplete tasks), $\overline{IWIP}_P$ is the average intellectual work in progress inventory for current period (P) and can be calculated using the following formula: $\overline{IWIP}_P = \left(\frac{IWIP + IWIP_{P-1}}{2}\right)$, R is the hourly engineering rate, and cc is the carrying cost of intellectual inventory defined as a percentage of the inventory value.

A reduction in the average lead time results in saving achieved by an output differential of a lead time delta.

$$LTR_{LT} = (\overline{LT}_B - \overline{LT}_Y) \times T_D \times R \tag{35}$$

LTR_{LT} represents saving associated with average lead time reduction, $\overline{LT}_B$ is the baseline average lead time, $\overline{LT}_Y$ is the year to date average lead time, and T_D is the daily throughput.

Lead time reduction saving is the sum of saving associated with a reduction in the number of non-touch days and saving associated with average lead time reduction.

$$LTR = LTR_{NTD} + LTR_{LT} \tag{36}$$

where LTR represents Lead time reduction.

Another lean engineering saving is intellectual inventory reduction (IR) that is a result of a reduction in intellectual work in progress inventory level (compared to the baseline inventory level) which leads to a carrying cost cutback (to reduce calculation fluctuations it can be carried on a three month rolling average basis) (Beauregard, Thomson, & Bhuiyan, 2008).

$$IR = (\left(IWIP_B \times \frac{M}{12}\right) - IWIP_Y) \times R \times cc \quad (37)$$

where IR represents intellectual inventory reduction, $IWIP_B$ is the baseline intellectual work in progress, and $IWIP_Y$ is the year to date intellectual work in progress.

Waste reduction (WR) is evaluated as the product of percentage waste improvement, available working time, and hourly engineering rate.

$$WR = \overline{WPCI} \times AHRS \times R \quad (38)$$

where WR represents waste reduction.

Throughput saving (TS) is calculated as throughput improvement, times the hourly engineering rate.

$$TS = TI \times R \quad (39)$$

where TS represents throughput saving.

And finally total lean savings is evaluated.

$$LS = LTR + IR + WR + TS \quad (40)$$

where LS represents lean savings.

It should be noted that in this model, the value of throughput saving is equal to the value of waste reduction, thus, one can remove savings resulting from throughput improvement from the lean savings equation (Equation 40) to get a more balanced value of lean savings.

5 CASE COMPANY IMPLEMENTATION RESULTS AND ANALYSIS

In this chapter, the results of the implementation of the LEPM model in a case company are discussed.

5.1 Case company description

The case studied is a small international engineering consultant company that provides civil design (architectural, structural, electrical, and mechanical), supervision, and construction services to its customers. The general design process in the case company comprises two phases. Phase 1 includes developing preliminary architectural design and phase 2 includes developing detailed structural and architectural designs. Due to confidentiality, the name of the company and details of data will remain undisclosed.

The case company, from now on referred to as company A, agreed to collect and provide data required for the model. During the measurement time, engineers involved in the company's construction design unit (architectural and structural design units) were asked to measure the amount of time they spend daily on selected project tasks discriminating between work, rework, and RNVA effort and record this data on the standard project timesheets of the company that are used to keep track of the time spent on design projects. These measured values were primarily verified by the managers of each engineering unit to avoid any measurement inconsistencies. The data collection process was conducted inside the company. The required data for the model was extracted from the project timesheets for the selected project tasks by the managers of each engineering unit. Finally, the data was validated by the senior manager of the company and was provided in order to have the engineering performance of the company measured using the LEPM model. Tasks studied are definable, tractable and are based on a high degree of legacy knowledge of the company (required activities and processing steps are equal across different tasks). Engineers determined the required values for fixed parameters of the model (such as $FTST$: average time required for a resource to setup for a task for the first time).

Differentiation of normal and extra iterations (rework) of work was done based on an internal consensus between engineers. These wasteful iterations can occur in the design process due to a number of reasons. Most of the wasteful design iterations occur in phase 2 of design inside the company. For example, structural analysis of the preliminary architectural design may impose changes and corrections to architectural design. These changes are required due to problems associated with the feasibility or manufacturability of the design proposed by architects (due to an engineering error made while trying to perfect the design). Changes made to any design can impose rework on already developed plans and increase the magnitude of work required to complete a task. These types of changes in design due to an engineering error are considered pure waste. Moreover, drawings are sent to municipal authorities to be the validated. If a drawing is rejected (e.g. due to violation of regulations), design changes and corrections are required by authorities. Revisions should be made and the design needs to be resubmitted to authorities in order to have it validated (this resubmission of design and having to redo the work already done is pure waste and is considered rework in the company).

5.2 Performance measurement at case company

The LEPM model is used to track performance at two different levels inside Company A; at the individual level and product family level. First, data regarding the performance of an architectural engineer that works on the tasks of the same product family is presented and discussed. Second, the performance of the design team comprising architectural and structural engineers with respect to a selected value stream is discussed.

Data regarding performance at individual level was provided by the company and the performance metrics were calculated (see Table 5-1). Eleven tasks were studied during the measurement period. The status of each value stream task at the end of the measurement period was determined and tasks were classified into model categories; 5 completed tasks, 5 active incomplete tasks, and 1 non-active incomplete task.

Value stream available working time was evaluated (308 hours) and decomposed into VA, NVA, and RNVA elements using available working time decomposition chart. Values of the predetermined parameters of the model provided by the engineering team are as follows:

$FTST$: Average time required for an engineer to setup for a task for the first time = 90 Minutes

$MTTP_i$: Minimum time required to effectively progress a task = 60 Minutes

ST: Average time required for an engineer to setup for a task: = 10 Minutes

RP: Inactivity period that requires the engineer to restart prior to charging to task = 5 Days

RT: Restart time = 45 Minutes

Rework is calculated as the sum of all the hours spent on correcting defective design.

Values of all lean engineering performance metrics are calculated using Microsoft Excel based on the LEPM model equations presented in previous chapter and the performance is compared to a previous performance of the company.

Table 5-1 Performance metrics calculated at individual level

Number of studied tasks	11
Number of completed tasks	5
Number of active incomplete tasks	5
Number of non-active incomplete tasks	1
Number of working days	44
Available working hours	308
Total hours charged to tasks	292.08
RNVA hours	15.92
Average charged hours	39.65
Average lead time days	25.8
Total number of touch days	65
Average touch days (completed task)	9.2
Total number of non-touch days	143
Average non-touch days (completed task)	16.6
Hours delivered	198.25
Touch time ratio	0.37
Intellectual work in progress hours	84.92
Wasted charged hours	8.91
First-time setup hours	15
Total setup hours	10.83
Total restart hours	6.75
Wasted setup hours	5.33
Total rework hours	34.33
Rework rate (completed tasks)	0.14
Waste hours	72.25
Total waste hours	97.08
Year to date percentage waste	31
Percentage waste improvement	10.5
Year to date throughput hours	210.9
Daily throughput hours	4.8
Throughput delivered per resource hour	0.68
Throughput improvement hours	32
Lead time reduction	$758
Intellectual inventory reduction	$339
Waste reduction	$1130
Total lean savings	$2227

Out of 308 hours of available working time, 292.08 hours are spent directly charging to the tasks and 15.92 hours (nearly 5% of the available working time) are spent on supporting RNVA activities. Average values of charged hours and lead time are calculated and shown in the Table 5-1. Based on the minimum time required to effectively progress a task ($MTTP_i$ parameter value) which is equal to 60 minutes for this type of tasks, each lead time day is classified as a touch day whether a minimum of 60 minutes is spent on the given task during that day by at least one engineer. Otherwise, that day is classified alternatively as a non-touch day, meaning, all charges made to the task on that day did not effectively progress the task towards completion (these charges are classified as wasted setup) and resources working on the task did not create any value, while they could have worked on other tasks creating value for stakeholders. A total number of 65 touch days and 143 non-touch days (for completed and active incomplete tasks) are calculated.

198.25 hours of available working time are spent on 5 completed tasks. The value of touch time ratio (for completed tasks) is about 0.37, meaning, 63% of the time tasks were idle in the engineering system receiving no charge at all or a charge that was lower than the $MTTP_i$ value. This low touch time ratio leads to a series of major issues discussed in previous chapter including longer lead times, longer queues, and increased amount of intellectual work in progress in the system. One of the potential areas that should be targeted for major improvement in the company is reducing the number of non-touch days. Intellectual work in progress hours (inventory) which is the total amount of time spent on 5 active incomplete tasks is calculated around 84.92 hours, that is 27% of the available working time. Wasted charged hours that is the total amount of time spent on 1 non-active incomplete task (customer cancelled the contract since the company was not able to deliver the design on time) is measured at 8.91 hours (that is 2% of the available working time). This time is classified as wasted charges since resource were used to charge to a task that ended up being non-value-added.

The total value of first-time setup is 15 hours (10 tasks started during measurement period each of them requiring an average of 90 minutes of first time setup). 10.83 hours of setup is calculated (65 charges are made to active tasks during touch days, each of them requiring 10 minutes of setup on average). Nine restarts are observed during the period, meaning nine times the engineer stopped working on a task for a period of more than RP=5 days and then came back charging to the task after this period. Thus, the engineer needs to restart for the task to be able to progress the task towards completion. The value of predetermined restart time for the company is RT=45 minutes, therefore, the total restart time is evaluated at 6.75 hours. As mentioned earlier, the values of parameters such as first-time setup, setup, restart, wasted setup and rework are calculated for completed and active incomplete tasks, disregarding non-active incomplete tasks since all effort spent on such tasks is already considered waste in the model. All charges to tasks on non-touch days are classified as wasted setup hours which are equal to 5.33 hours for the period. Rework iterations for all tasks summed up to around 34.33 hours with a rework rate of nearly 14% for completed tasks. The aggregated value of first-time setup, setup, restart, wasted setup and rework which constitutes the value of waste is about 72.25 hours (for completed tasks and active incomplete tasks).

A processing time decomposition chart was used to break down average processing time (average processing time can be calculated using Equation 3) of completed tasks into value-added, non-value-added, and required non-value-added efforts. Figure 5-1 depicts the percentage value-added, non-value-added, and required non-value-added effort charged on average to a completed task. The average non-value-added effort is further decomposed into average first-time setup, setup, restart, wasted setup and rework which can be calculated respectively using equations 12, 13, 14, 15, and 16. Figure 5-2 shows percentage first-time setup, setup, restart, wasted setup and rework incurred on average while processing a completed task in the first value stream during the period of measurement.

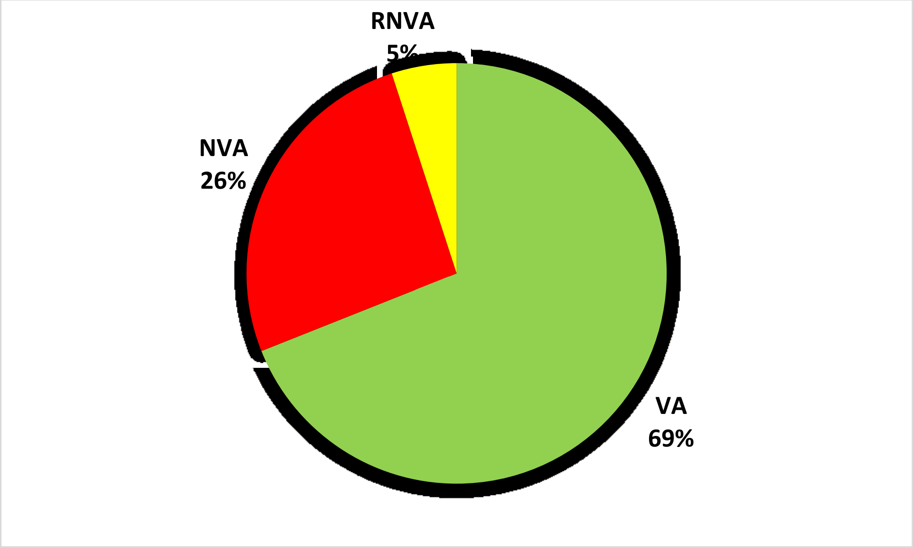


Figure 5-1 Percentage VA, NVA, RNVA average occurrence in a completed task (1st VS)

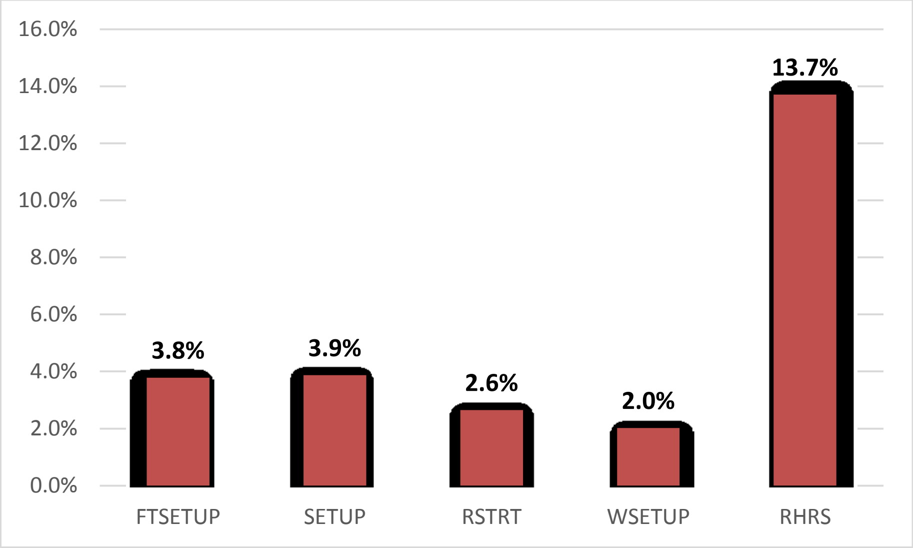


Figure 5-2 Percentage NVA elements average occurrence in a completed task (1st VS)

Finally by adding the values of wasted charged hours (8.91 hours) and RNVA time (15.92) to the value of previously calculated waste, the total amount of waste in the system is evaluated which is equal to 97.08 hours that is around 31% of the value stream available time.

Now the performance is compared to a previous performance of the company (baseline). During the period of measurement, the amount of total waste in engineering tasks is reduced by 10.5% and engineering throughput is improved by 32 hours. Lead time reduction, intellectual inventory reduction, waste reduction and throughput saving are evaluated using model equation and are represented in the Table 5-1 (R: The hourly engineering rate for the company is equal to 35 dollars, and cc: Carrying cost of intellectual inventory for the company is equal to 25% of the inventory value). The total value of lean savings is calculated at $2227 for this period inside the company.

Table 5-2 summarized data regarding performance metrics of the second value stream. Seven tasks of the same product family were studied. A total of 5 engineers charged to the tasks with an average of 4.33 (about 5) engineers charging to a completed task. Performance metrics and lean engineering savings represented in the Table 5-2 are calculated in the same manner as explained earlier for first value stream using model equations. For this value stream with 658.16 hours of available working time, 623.91 hours are spent directly charging to the tasks (completed and active incomplete tasks) and 34.25 hours (around 5% of the time) is spent on RNVA activities.

A total number of 121 touch days and 52 non-touch days are calculated (for completed and active incomplete tasks). Total charge to 5 completed tasks is equal to 398.08 hours. The value of touch time ratio (for completed tasks) is about 0.75 meaning that only 25% of the time tasks are idle in the system receiving no charge at all or a charge that is lower than the $MTTP_i$ value.

Table 5-2 Performance metrics calculated at product family level

Number of studied tasks	7
Number of completed tasks	3
Number of active incomplete tasks	3
Number of non-active incomplete tasks	1
Number of working days	44
Available working hours	658.16
Total hours charged to tasks	623.91
RNVA hours	34.25
Average charged hours	132.68
Average lead time days	32.66
Total number of touch days	121
Average touch days (completed task)	23.67
Total number of non-touch days	52
Average non-touch days (completed task)	9
Hours delivered	398.08
Touch time ratio	0.75
Intellectual work in progress hours	180.5
Wasted charged hours	45.33
First-time setup hours	37.5
Total setup hours	32.66
Total restart hours	21
Wasted setup hours	5.25
Total rework hours	111.08
Rework rate (completed tasks)	0.20
Waste hours	207.5
Total waste hours	287.08
Year to date percentage waste	44
Percentage waste improvement	9.3
Year to date throughput hours	371.08
Daily throughput hours	8.4337
Throughput delivered per resource hour	0.5638
Throughput improvement hours	61
Lead time reduction	$2349
Intellectual inventory reduction	$175
Waste reduction	$2142
Total lean savings	$4666

Value of touch time ratio for second value stream (0.75) is significantly greater than the first one (0.37) owing to the fact that the number of touch days are relatively higher in second value stream, therefore, idleness is lower for the tasks. Intellectual work in progress hours (inventory) is 180.5 hours, which is 27% of the available working time.

The wasted charged hours parameter is calculated at 45.33 hours. 37.5 hours of first-time setup is evaluated (a total of 25 first time setups occurred). About 32.66 hours of setup is calculated (196 charges are made to active tasks during touch days). A total of 28 restarts are observed during this period, therefore, the total restart time is evaluated at 21 hours. Engineers charged 5.25 hours to tasks on non-touch days (wasted setup). Total rework is 111.08 hours with a rework rate of nearly 20% for completed tasks. The amount of total waste in the system is evaluated at 287.08 hours that is 44% of the values stream available working time.

Figure 5-3 illustrates the percentage value-added, non-value-added, and required non-value-added effort charged on average to a completed task. Figure 5-4 shows percentage NVA elements occurrence in a completed task in the second value stream during the period of measurement.

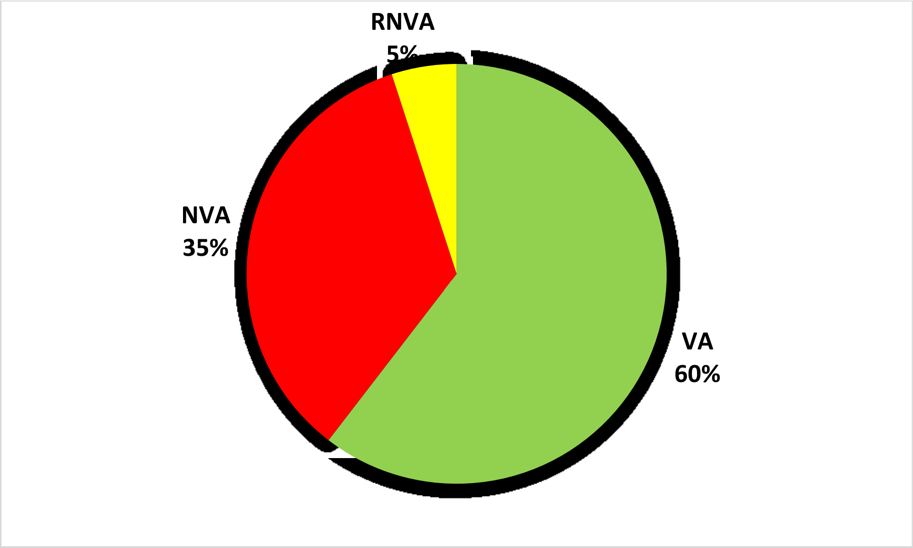


Figure 5-3 Percentage VA, NVA, RNVA average occurrence in a completed task (2nd VS)

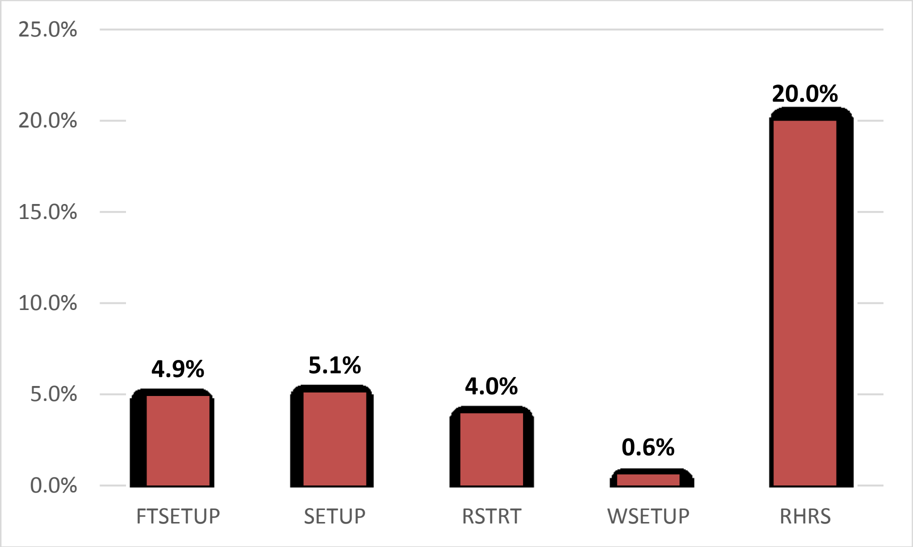


Figure 5-4 Percentage NVA elements average occurrence in a completed task (2nd VS)

By calculating performance metrics for this period, it is observed that the amount of total waste for this value stream is reduced by 9%, throughput is improved by 61 hours, and the company saved $4666 during this period.

5.3 Performance analysis and implications

In this section the results of performance measurement at Company A are discussed and performances of the two value streams are compared for this period.

A higher number of engineers (resources) working on tasks of the second value stream (an average of 4.16 engineers working on second value stream tasks compared to 1 engineer for the first value stream) and charging tasks in a more continuous manner resulted in a significantly greater touch time ratio (a task in the second value stream is on average 38% less idle). However, since too many job handoffs occurred in the workflow of the second value stream, engineers spent a relatively greater amount of time on restarts before continuing to charge to the tasks again.

A higher rework rate for completed tasks is observed in the second value stream (20% compared to 14% in first value stream) that is partly due to the lack of efficient communication between engineers which sometimes resulted in an engineer developing a design that was already changed since he was not informed of the change at the right time.

A combination of longer lead times, ineffective scheduling, change in priorities, running too many projects at the same time, engineers tending to work on more tasks at the same time to be positively evaluated, too many job handoffs, and interruptions in the workflow, will lead to a higher amount of NVA elements, and task idleness in the system. Thus, more time is spent on

NVA efforts (first-time setup, setup, restart, wasted setup and rework) while this time could be minimized or eliminated to be used to create value.

Setup time is calculated each time a charge is made to a task, thus, as the number of resources increases, setup time is also increased. Furthermore, processing tasks using smaller charges requires more setup time (Fullerton & Wempe, 2009). In order to reduce setup hours in the engineering process, companies need to reduce average time required for setup, reduce the number of charges to tasks, or process tasks using larger charges.

The total amount of waste in the second value stream is 13% higher (44% compared to 31% in the first value stream). It has to be noted that as the number of engineers working on tasks increases, consequently due to an increase in the number of charges, job switching, and job hand-offs, the values of first-time setup, setups, restarts, and rework is increased, therefore, more waste is created in the engineering system. Thus, while the number of resources working on the tasks is increased, an effective scheduling and communication must be put in place in order to control and minimize creation of such wasteful activities.

During this period, by the use of model, improvement in performance is observed in every dimension in both value streams due to a preliminary implementation of lean principles in the engineering department of the company. The management agrees that there still remains a major opportunity for improvement in their engineering department if the remaining obstacles are tackled as it is just the start for them on their path to transform into a lean engineering company.

The implementation of the LEPM model in Company A enabled performance measurement at different levels. It provided visibility on the waste hidden in their engineering process and provided a tool for measuring that waste and tracking improvement efforts. As a result, setting targets inside the company for improvement is now possible for the manager as the model metrics provide a unified measurement system to coordinate all engineering effort inside engineering department. Now, they can use the model to measure effects of different scheduling and work processing approaches on performance of their engineering department and identify best possible practice that suits their strategies.

One of the potential areas that should be immediately targeted for improvement is reducing the number of non-touch days for the first value stream (by effective scheduling and changing work approach). Engineers have begun to correct their work behavior to minimize waste parameters. Before, engineers were interested in increasing the number of tasks they were working on at the same time, instead of focusing on completing already started tasks and delivering them.

One significant achievement of model introduction and implementation in Company A was to bring attention to existence of phenomena such as setups, restarts, wasted charged hours, and other waste parameters in the engineering process. Upon introduction, engineers quickly acknowledged the existence of such wasteful phenomena and stated that they occur in everyday work. One engineer said “there was never any attempt made to discriminate these wasteful efforts from normal work. No one ever evaluated how much time is spent on such wasteful activities because they are considered to be an inherent part of normal work and not to be waste”.

5.4 Summary

The implementation of the LEPM model in the engineering process of a company that is different in size (small engineering consultant company vs. major aerospace company) and industry (civil vs. aerospace) compared to the company where the original model was designed for and implemented, validates the fact that the new version of the model is applicable to the engineering process in general and is not limited to any specific engineering process or organization. The use of performance metrics and phenomena that exist in any engineering process, modification of equations, and the use of flexible parameters for which the values are determined in the company where the model is implemented, allow the model to be tailored and adapted to the characteristics of any engineering process and company.

Performance measurement can influence organizational behavior to coordinate and align engineering effort with the strategies of the organization (Neely, Gregory, & Platts, 2005). By developing new performance indicators that measure and promote lean initiatives in the engineering process, hidden omnipresent waste in engineering work becomes transparent, therefore, dimensions of work that are critical to lean transformation are highlighted to receive more attention of engineers thus enabling more improvement.

Lean tools and techniques impact different dimensions of work, hence, effective decision making would be a complex task for managers if proper measures that can consolidate all these effects into one scalar are not available (Bayou & Korvin, 2008). The LEPM model provides managers insight into selection of the appropriate lean tools and techniques by measuring the effects of implementation of such tools and techniques on performance. Therefore, it enables benchmarking of lean performance at different levels and identifies the best practice.

6 CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

In this chapter, conclusions of the research, limitations, and future research opportunities are discussed.

6.1 Conclusions

In this thesis, a lean engineering performance measurement (LEPM) model was developed to address the need for a model that can measure the performance effects of implementing lean initiatives in the engineering process. This research is aimed to improve the model developed by Beauregard, Thomson, and Bhuiyan (2008) for an aerospace engineering company in terms of measurement effectivity and model applicability in order to introduce a new model that can measure the effects of adopting lean initiatives in any engineering process regardless of the industry or size of the organization.

As part of the improvement, the model equations were modified; calculation of engineering waste is extended to take into account entire value stream tasks (vs completed task); new metrics are developed that account for those types of waste that are unique to the engineering process and had received no attention in the design of existing measurement methods (most of the times only waste concepts of manufacturing are considered and transferred to product development.); a decomposition chart is developed for available working time that enables breaking down engineering effort into VA, NVA, and RNVA elements. The most significant contribution of this research is the development of new performance metrics and the decomposition chart. The author believes lack of such metrics and a decomposition chart that provide visibility to hidden waste inherent in the engineering effort is one of the reasons why such wasteful aspects are neglected in the first place and are not targeted for immediate improvement.

Furthermore, performance metrics are properly linked and are presented as a model (and not some individual metrics) that can measure engineering performance at different organizational levels from a lean perspective and promotes lean in engineering. To measure leanness, most existing methods treat lean as a set of some tools and base their evaluation on a subjective assessment, while the LEPM model treats lean as a holistic system and objectively measures performance. Hence, performance effects of implementing lean tools and techniques into engineering process can be evaluated to track progress achieved towards fulfillment of lean goals such as waste elimination, lead time reduction, intellectual inventory reduction, and throughput improvement and also to identify best practice.

The original model was implemented in the engine design prcoess of a major aerospace company (Beauregard, 2010). The new model presented here was successfully implemented in civil design process of an engineering consultant company to measure lean engineering performance which validates the general applicability of the new model.

Although the model measures performance of engineering process from a lean perspective, since the performance dimensions being measured and targeted for improvement (waste elimination, lead time reduction, intellectual inventory reduction, and throughput improvement) are of high importance for any engineering process, the model can also be implemented as a performance measurement system by companies who are seeking continuous improvement (and not directly pursuing a lean process) to measure and track engineering performance. Phenomena described and performance metrics developed for the model do not only exist in the engineering, but in the knowledge-based processes as well, therefore, the model can also be implemented in knowledge-based processes as a performance measurement tool.

While implementing the model to measure the performance of knowledge-based processes of projects that are highly research intensive and are classified as research projects rather than product development projects, the focus should be on minimizing waste. Although the required activities of such projects are less known beforehand (due to higher uncertainty associated with research projects) and the projects are more unique in nature which can lead to performance variations across different projects (e.g. on lead time dimension), this would not affect the importance of minimizing and eliminating NVA and RNVA activities that are performed while executing these projects. The amount of time spent on activities such as first-time setup, setup, restart, wasted setup, and rework that exist in any type of knowledge-based process creates no value, therefore, it is a pure waste of time and resources of the company. Using resources to deliver knowledge that ends up being of no value (classified as wasted charged hours in the model) for the stakeholders is also a huge waste of time and resources. The amount of time that is spent on performing necessary tasks such as research and development (R&D) and other supporting tasks (RNVA time) such as creating presentations, reports, and attending meetings should be minimized (to a certain extent when it comes to R&D) considering that resources can use this time in order to directly charge and progress the tasks towards completion. To achieve improvements on such wasteful dimension in order to increase the efficiency of the process, time spent on such wasteful activities should be measured, controlled, and targeted for improvement. The LEPM model provides a tool that can measure performance and track improvements on such wasteful dimensions.

In multiple discussions on the LEPM model with academics, managers, engineers, and fellow researchers, they all admitted that waste phenomena introduced in the model exist as inherent parts of their normal everyday work, however, as in the case of the company, most admitted that they had never made any effort to control and reduce the amount of time spent on such wasteful activities as they are considered as part of normal effort and not waste.

6.2 Limitations and future research

The LEPM model is best applicable to measure performance of engineering tasks that are definable, tractable, and are based on a high degree of legacy knowledge where required processing steps and activities are known beforehand where benchmarking performance is more appropriate.

For future research, an optimization model for scheduling engineering tasks can be developed which takes into account performance metrics of LEPM model while minimizes engineering waste and maximizes lean engineering performance.

The relationship between alternative scheduling algorithms and lean engineering performance can be studied in order to identify optimum scheduling algorithm.

The performance effect of implementing lean tools and techniques in engineering process can also be measured and analyzed.

If required data is available, the model can be implemented to benchmark leanness of performance of engineering processes within and across industries to identify best in class processes. Efficiency of product development processes, time spent on RNVA activities, tasks classified in wasted charges category, and magnitude of waste metrics can also be examined in detail and analyzed.

BIBLIOGRAPHY

Baines, T. S., Lightfoot, H., Williams, G. M., & Greenough, R. (2006). State-of-the-art in lean design engineering: A literature review on white collar lean. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 220(9)*, 1539-1547.

Bauch, C. (2004). *Lean Product Development: making waste transparent.* Diploma thesis, Massachusetts Institute of Technology.

Bayou, M.E., & Korvin, A. D. (2008). Measuring the leanness of manufacturing systems—a case study of Ford Motor Company and General Motors. *Journal of Engineering and Technology Management, 25(4)*, 287-304.

Beauregard, Y. (2010). A multi-criteria performance study of lean engineering. *Thesis (Ph. D.) Department of Mechanical and Industrial Engineering, Concordia University*.

Beauregard, Y., Thomson, V., & Bhuiyan, N. (2008). Lean engineering logistics: load leveling of design jobs with capacity considerations. *Canadian Aeronautical and Space Journal, 54(2)*, 19-33.

Beisheim, N., & Stotz, F. (2013). Key Performance Indicators for Design and Engineering. In G. R. Josip Stjepandić, *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment* (pp. 341-351). Springer London.

Bhasin, S. (2011). Performance of organisations treating lean as an ideology. *Business Process Management Journal, 17 (6)*, 986 - 1011.

Brown, M. G., & Svenson, R. A. (1998). Measuring R&D productivity. *Research-Technology Management, 41(6)*, 30-35.

Browning, T. R. (2000). Value-based product development: refocusing lean. *Engineering Management Society, 2000. Proceedings of the 2000 IEEE*, 168-172.

Chiesa, V., & Masella, C. (1996). Searching for an effective measure of R&D performance. *Management Decision, 34(7)*, 49-57.

Chiesa, V., Frattini, F., Lazzarotti, V., & Manzini, R. (2009). Performance measurement of research and development activities. *European Journal of Innovation Management, 12(1)*, 25-61.

Comm, C. L., & Mathaisel, D. F. (2000). A paradigm for benchmarking lean initiatives for quality improvement. *Benchmarking: An International Journal, 7(2)*, 118-128.

Costa, J. M., Rossi, M., Rebentisch, E., Terzic, S., Taisch, M., & Nightingale, D. (2014). What to Measure for Success in Lean System Engineering Programs? *Procedia Computer Science, 28*, 789-798.

Crute, V., Ward, Y., Brown, S., & Graves, A. (2003). Implementing Lean in aerospace—challenging the assumptions and understanding the challenges. *Technovation, 23(12)*, 917-928.

Driva, H., Pawar, K., & Menon, U. (2000). Measuring product development performance in manufacturing organisations. *International Journal of Production Economics, 63(2)*, 147-159.

Driva, H., Pawar, K. S., & Menon, U. (2001). Performance evaluation of new product development from a company perspective. *Integrated Manufacturing Systems, 12(5)*, 368-378.

Fullerton, R. R., & Wempe, W. F. (2009). Lean manufacturing, non-financial performance measures, and financial performance. *International Journal of Operations & Production Management, 29(3)*, 214-240.

Haque, B. (2003). Lean engineering in the aerospace industry. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 217 (10)*, 1409-1420.

Haque, B., & Moore, M. J. (2004). Measures of performance for lean product introduction in the aerospace industry. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 218(10)*, 1387-1398.

Hines, P., Holweg, M., & Rich, N. (2004). Learning to evolve: A review of contemporary lean thinking. *International Journal of Operations & Production Management, 24(10)*, 994-1011.

Hoppmann, J., Rebentisch, E., Dombrowski, U., & Zahn, T. (2011). A Framework for Organizing Lean Product Development. *Engineering Management Journal, 23(1)*.

Karlsson, C., & Åhlström, P. (1996). The difficult path to lean product development. *Journal of Product Innovation Management, 13(4)*, 283-295.

Kato, J. (2005). *Development of a Process for Continuous Creation of Lean Value in Product Development Organizations.* MS Thesis in Mechanical Engineering, Massachusetts Institute of Technology.

Kerssens-van Drongelen, I. C., & Cooke, A. (1997). Design principles for the development of measurement systems for research and development processes. *R&D Management, 27(4)*, 345-357.

Kerssens-van Drongelen, I., Nixon, B., & Pearson, A. (2000). Performance measurement in industrial R&D. *International Journal of Management Reviews, 2(2)*, 111-143.

Kuczmarski, T. D. (2001). Five fatal flaws of innovation metrics. *Marketing Management, 10(1)*, 34-39.

Lander, E., & Liker, J. K. (2007). The Toyota Production System and art: making highly customized and creative products the Toyota way. *International Journal of Production Research, 45(16)*, 3681–3698.

Liker, J. K., & Morgan, J. M. (2006). The Toyota way in services: the case of lean product development. *The Academy of Management Perspectives 20(2)*, 5-20.

Mascarenhas Hornos da Costa, J., Oehmen, J., Rebentisch, E., & Nightingale, D. (2014). Toward a better comprehension of Lean metrics for research and product development management. *R&D Management, 44(4)*, 370-383.

McManus, H. L. (2005). *Product Development Value Stream Mapping (PDVSM) Manual.* Cambridge: The Lean Aerospace Initiative, Massachusetts Institute of Technology.

McManus, H., Haggerty, A., & Murman, E. (2005). Lean Engineering: Doing the Right Thing Right. *1st International Conference on Innovation and Integration in Aerospace Sciences, 4-5 August.* Belfast, Northern Ireland.

Neely, A., Gregory, M., & Platts, K. (2005). Performance measurement system design A literature review and research agenda. *International Journal of Operations & Production Management, 25 (12)*, 1228-1263.

Oehmen, J., & Rebentisch, E. (2010). Waste in lean product development. *LAI Paper Series Lean Product Development for Practitioners, Cambridge, MA, LAI and MIT*.

Oehmen, J., Oppenheim, B. W., Secor, D., Norman, E., Rebentisch, E., Sopko, J. A., ... & Driessnack, J. (2012). *The Guide to Lean Enablers for Managing Engineering Programs, Version 1.* Cambridge, MA: Joint MIT-PMI-INCOSE Community of Practice on Lean in Program Management,.

Oppenheim, B. W. (2004). Lean Product Development Flow. *Systems Engineering, 7(4),* 352-376.

Parry, G. C., & Turner, C. E. (2006). Application of lean visual process management tools. *Production Planning & Control, 17(1)*, 77-86.

Shah, R., & Ward, P. T. (2003). Lean manufacturing: context, practice bundles, and performance. *Journal of Operations Management, 21(2)*, 129-149.

Soriano-Meier, H., & Forrester, P. L. (2002). A model for evaluating the degree of leanness of manufacturing firms. *Integrated Manufacturing Systems, 13(2)*, 104-109.

Tatikonda, M. V. (2008). Product Development Performance Measurement. In S. K. Christoph H. Loch, *Handbook of New Product Development Management* (pp. 200-215). Oxford, United Kingdom: Elsevier.

Teresko, J. (2008). The Future of R&D: Leveraging Innovation. *Industry Week, Penton Publishing, Cleveland, Ohio, USA, May 2008, Downloaded from http://www.goldensegroupinc.com/CompPub/Quotations/the-future-of-research-and-development-leveraging-innovation-Q33.shtml*.

Womack, J. P., & Jones, D. T. (2003). *Banish Waste and Create Wealth in Your Corporation, Revised and Updated.* New York: Free Press.

APPENDIX A

Here, a sample of daily charges (time is measured in minutes) collected by the company that is used as input for LEPM model is provided.

Table Appendix-1 Sample of daily charges collected by Company A

Days	Tasks				
	Task 1001	Task 1002	Task 1003	Task 1004	Task 1005
1	370	-	-	-	-
2	400	-	-	-	-
3	350	30	-	-	-
4	-	385	-	-	-
5	-	415	-	-	-
6					
7					
8	200	105	45	-	-
9	-	-	415	-	-
10	-	-	410	-	-
11	-	-	45	180	160
12	-	-	-	300	110
13					
14					
15	-	-	-	365	50
16	-	-	-	300	75
17	-	-	-	-	400
18	25	-	-	-	355
19	410	-	-	-	-
20					
21					
22	165	250	-	-	-
23	190	205	-	-	-
24	-	410	-	-	-
25	-	300	-	-	-
26	165	-	-	-	-
27					
28					
29	-	-	-	-	-
30	-	**Delivered**	-	-	-
31	**Delivered**	-	-	-	220

APPENDIX B

Here, a sample of calculation of model metrics for two tasks is provided.

Table Appendix-2 Sample of calculation of model metrics using Microsoft Excel

Metric	Task 1001	T1002
CHRS	2275	2100
Status	Completed	Completed
Lead time	23	20
TD	8	7
NTD	15	13
TTR	0.347826087	0.35
HRD	2275	2100
IWIP	-	-
WCHRS	-	-
FTSETUP	90	90
SETUP	80	70
#RSTRT	1	1
RSTRT	45	45
WSETUP	25	30
RHRS	365	205
WASTE	605	440
WPC	0.265934066	0.20952381
PT_i	2275	2100