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PRODUCTIVITY MODELING

A Major Qualifying Project Report
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II. Abstract

The goal of this project was to model productivity within a new product development environment to illustrate the impacts of lean initiatives. After researching productivity models, a model was constructed and applied to a hypothetical product development organization. Lean initiatives were then applied to the product development case study and the impacts on productivity were analyzed using the productivity index model. The results demonstrated how such models can be used to measure the effectiveness of lean in new product development.

1.0 Introduction

Over the past ninety years productivity measurement has taken on many forms and has gone through many iterations. These include the first modern-age models like Cobb-Douglas[1], to the widely used Koss-Lewis[2] models, to the modern complex frontier based DEA models similar to those used by Mahadevan[3]. Although productivity models, theories, and applications have evolved over the decades, several things have held true over time. First, accurately measuring productivity has always been a concern and a significant challenge for companies, productivity experts, and theorists. Complex variables, variations in data sets, and incomplete, unverified, or inaccurate data have led to the development of numerous models. However, none are able to account for all the above factors. Second, there is no standard model or models for given industries, nor are there agreed upon methods for selecting the appropriate model to be used for the application. This means the selection, development, and use of productivity models is strictly determined by the user. As a result productivity is nearly impossible to compare between models, industries, and companies[4].

Historically, manufacturing and production have been the focus of productivity measurement. With the drive to increase efficiency, reduce costs, and improve quality corporate-wide, it is essential to analyze productivity across all business segments in order to identify areas of improvement and measure results. One of the most difficult areas to measure productivity has been new product development. Griliches cites his previous work as "identifying and describing many of the difficulties that haunt this research today"[5]. Many of the factors that contribute to the outputs (benefits) and inputs (costs) can be quite complex and difficult to quantify. The lack of measurable and

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[1] Sumanth,: "Productivity Engineering and Management**",** McGraw Hill Book Company, 1987
[2] Koss, Lewis: "Productivity or Efficiency – Measuring What We Really Want", National Productivity Review
[3] Mahadevan: "New Currents in Productivity Analysis Where to Now?", Asian Productivity Organization, 2002
[4] Griliches: "R&D and Productivity: The Econometric Evidence", University of Chicago Press, 1998
[5] Griliches: "R&D and Productivity: The Econometric Evidence", University of Chicago Press, 1998

available data, variations in the number and types of factors, and no standards for modeling productivity in product development have contributed to the lack of success and effort in measuring productivity in product development. Although an all encompassing productivity model may not exist to allow for comparisons between industries and companies, we can develop an accurate productivity model to measure a company's performance over different periods in relatively simple terms using a Koss-Lewis model. The Koss-Lewis model is a Total Productivity Index model with the ability to weight individual factors. It does differ from traditional index models in that the model does not calculate a total ratio of inputs to outputs, rather the model uses multiple productivity factors to derive a total productivity factor.[6]

The motivation to reduce costs, improve quality, reduce cycle time, and improve the overall efficiency of product development has led to the adaptation of traditional manufacturing tools such as Lean to the new product development environment. In recent years, many organizations have been highly successful adapting lean principles and implementing them in a product development environment, resulting in benefits such as reduced product development time, reduced rework costs, and higher revenue attributable to new or improved products. Lean initiatives such as improved scheduling and planning, parts/material/supplier management, identifying waste through process mapping and eliminating it, and changes in engineering practices and standards have the potential to generate marked improvements in productivity. Because lean initiatives require substantial effort, it is important to be able to measure improvements.

The goal of this Major Qualifying Project (MQP) is to develop a productivity model to examine how lean improvements might affect productivity, providing a way to measure the effects of lean improvements. Such models and analysis help to demonstrate success as well as areas that require further improvement. To achieve this goal the first step was to understand and summarize the history and methods of productivity

[6] Koss, Lewis: "Productivity or Efficiency – Measuring What We Really Want", National Productivity Review

measurement. Second, a model that can be used to accurately measure the productivity of product development business units was selected and developed. The third step was to identify and comprehend lean initiatives that can be adapted to new product development. Lastly, the potential impacts of lean initiatives on productivity in a new product development environment were explored using the model created, applied to a hypothetical case study.

2.0 Background Research

In order to determine how to measure productivity in product development it is necessary to understand what a productivity model is and what types of productivity models exist. This section provides a brief history and overview of productivity measurement and several models that were researched.

2.1 Productivity Measurements

The earliest productivity models of the modern industrial age can be traced back to the 1920's and are largely attributed to Paul Douglas and Charles Cobb. The Cobb-Douglas based models are still in use today as a simple productivity model for rough calculations or on a micro-level for individual processes[7]. These early models simply expressed productivity as a ratio of Production to Labor plus Capital, as shown below

$$P = \frac{\text{Production}}{\text{Capital and Labor}}$$

With the increased use of technology, variation in production methods and business complexity that changed the manufacturing industries in the late 1950's through the mid 1970's, these early models could no longer accurately account for total productivity. During this time period there was an explosion of new theories and proposed models based on "Total Factor Productivity". These models strived to expand the basic principle that productivity equals production divided by labor and capital to include additional attributes such as inventory, maintenance, WIP, R&D, employee benefits, fixed capital, investor contributions, among others[8]. Some of the prevalent models developed during this period were Kendrick & Creamer[9], Craig & Harris[10],

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[7] Sumanth,: "Productivity Engineering and Management**",** McGraw Hill Book Company, 1987
[8] Sumanth,: "Productivity Engineering and Management**",** McGraw Hill Book Company, 1987
[9] Kendrick, Creamer,: "Measuring Company Productivity: Handbook with Case Studies**",** Studies in Business Economics, No. 89, National Industrial Conference Board, 1965

Hines[11], and Sumanth[12]. Probably the most popular and widely used was the Taylor-Davis[13] model. The Taylor-Davis model is an index based model derived from the simple productivity ratio. It is considered a “Total” model, but differs from many total models in it’s consideration of raw materials.

Similar to the 1960’s and 1970’s, the 1990’s to present have seen an increase in technology use, changes in production methods, and more importantly a global economy; which has drastically changed business models. This, in turn has led to another revolution in Productivity Model theories. This new age of productivity modeling has led to an abundance of different theories and models, each with their own unique adaptations to the early Total Factor Productivity Models. While the latest models may be tailored for specific industries, processes, or business models, they do have one common thread that led to their development. Previous models were not able to adequately handle the increasing number of inputs and outputs necessary to accurately trace productivity, nor could they factor the individual inputs and outputs by the weight they carry in affecting productivity.

Modern model developers and theorists have given different names to similar techniques, which have proven to be quite confusing when trying to analyze the different methods and types of productivity models. The most notable, and obvious difference among models is the number of and type of variables used in the model, which makes the basic model different. The calculation order of the variables can also differ among the models, which affects the results. The base theoretical framework for modern productivity models could be cost theory (activity volume measured by output volume) or production theory (activity volume measured by input volume). The accounting technique applied to the model also sets each model apart from each other. Typical

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[10] Craig, Harris: “Total Productivity Measurement at the Firm Level”, Sloan Management Review, Vol. 14, No. 3, 1973

[11] Hines: “Guidelines for Implementing Productivity Measurement”, Industrial Engineering, Vol. 8, No. 6, 1976

[12] Sumanth,: “Productivity Engineering and Management**”,** McGraw Hill Book Company, 1987

accounting techniques used are; ratio accounting, variance accounting, and accounting form[14]. The adjustability type (fixed or adjustable) is another factor that differs between models. In an adjustable model the core characteristics can be changed allowing it to be compared with other models. In a fixed model characteristics are held constant.

Even though today's models are unique and can vary greatly, they are based on the same principles for improving on earlier models. That principle being the inputs and outputs are multi-functional (qualitative, quantitative, subjective), multi-variable attributes (time based, interrelated, subcomponents), which should be scaled and weighted on an individual basis. A basic representation of the modern principle of productivity models is shown below, when total factor productivity (TFP) is a ratio of weighted output to weighted input variables:

$$\text{TFP} = \frac{\text{f(sum of scaled, weighted output attributes)}}{\text{f(sum of scaled, weighted input attributes)}}$$

$$\text{TFP} = \frac{\text{f}(\Sigma_o (swA)_o}{\text{f}(\Sigma_i (swA)_i}$$

Attempts have been made to classify current productivity models based on their core characteristics, methods, and results. Although the classifications are not widely accepted or recognized as a standard they are useful in understanding the different methodologies and comparing some models with each other. Mahadevan claimed most modern productivity models could be categorized into two main types, the "Frontier Approach", and "Non-Frontier" approach[15]. Within each of these main categories there are various subcategories that reflect for example, differing calculations and accounting methods. Within the Frontier Approach subcategories include Parametric Estimation and Non-Parametric Estimation, each having their own further breakdown of subcategories.

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[13] Taylor, Davis,: "Corporate Productivity-Getting It All Together**",** Industrial Engineering, Vol. 9, No. 3, 1977

[14] Saari: "Productivity: Theory and Measurement in Business", European Productivity Conference, 2006

Mahadevan proposed that the Non-Frontier approach could also be broken down into Parametric Estimation and Non-Parametric Estimation categories, each with their own subcategories.

The core difference between Frontier and Non-Frontier measurements is the ability of the Frontier models to impose boundaries to the production or cost function. These binding functions give the Frontier based models the capability to provide the optimal outputs from the given set of inputs, whereas the Non-Frontier based models provide the average or normal outputs from the given set of inputs. Another key difference that distinguishes the Frontier models is the approach of including technical efficiency in the TFP growth measure. Non-Frontier based models assume that what is being measured is already efficient. Both the Frontier and Non-Frontier TFP growth measures do include "technical progress", which captures technical improvements in inputs, but only the Frontier models directly measure gains in technical efficiency[16]. Frontier models can also be used for benchmarking against other firms, industry standards, or its own maximum potential because of the boundary functions inherent in the model's design. It's not possible to accurately benchmark using Non-Frontier models.

Even though both model bases have differing core theories and structures they each use either parametric estimation or non-parametric estimation. Generally, in parametric estimation some form of the model is fixed. It could be the number and type of inputs and outputs, the weighting or scales of inputs and outputs, or the calculation order. In non-parametric estimation the model is adjustable (not-fixed), and provides fewer assumptions and more flexibility. However, non-parametric estimation can be more complex and can lead to greater error if not carefully designed.

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[15] Mahadevan: "New Currents in Productivity Analysis Where to Now?", Asian Productivity Organization, 2002

[16] Mahadevan: "New Currents in Productivity Analysis Where to Now?", Asian Productivity Organization, 2002

Non-Frontier parametric estimation models, commonly referred to as Index Methods/Models are typically the simplest and easiest models to use, understand, and calculate, but provide few inputs and assume a proportional input to output growth ratio. This provides for inaccurate Total Factor Productivity measurements and should be used for approximation only. Non-Frontier non-parametric estimation models are a step up from the former, and in some cases are simply Index Models with constraints lifted to remove the proportional biasing.

As in Non-Frontier models, Frontier models utilize both parametric and non-parametric estimating. However, both the parametric and non-parametric models are equally complex and neither one has a clear advantage over the other. Frontier based parametric models commonly consist of Stochastic and Bayesian based estimation methods. Non-parametric Frontier based models are typically classified by their Data Envelopment Analysis (DEA) approach.

Saari proposed a simpler method for categorizing productivity models. He has suggested that all models fall into three categories; Productivity Index Models, PPPV Models (Productivity, Prices, Volume), and PPPR (Productivity, Price Recovery)[17]

In summary, there is not a current standard or preferred method or model for calculating productivity at the firm or process level. Modern productivity theorists and experts do not agree on how to categorize the types of models and theories, or provide recommendations for their uses and applications. The user must select the type of model most appropriate to the inputs and outputs available, objectives, and which model will provide the best results.

[17] Saari: "Productivity: Theory and Measurement in Business", European Productivity Conference, 2006

2.1.1 Taylor – Davis Model (1977) [18]

The Total Factor Productivity (TFP) of a firm is measured as follows:

$$TFP = \frac{(S + C + MP) - E}{(W + B) + [(K_w + K_f) F_b d_f]}$$

$$TFP = \frac{\text{Total value - added output}}{\text{total input (capital and labor)}}$$

Where:

S = Net adjusted Sales
= Sales in dollars for the period/(price deflator / 100)
C = Inventory Change
= Sum of inventory changes for raw materials, finished goods, ½ work in process for raw materials, and ½ work in process for finished goods.
MP = Manufacturing Plant
= This includes items that are available outside of the firm but they are produced internally such as maintenance, machinery, equipment, and research and development.
E = Exclusions
= Materials and services that are purchased outside the firm
W = Wages and Salaries
= Labor costs
B = Benefits
= Includes vacations, benefits, insurance, sickness, social security, bonuses, retirement, and profit shearing
K_w = Working Capital
= Cash + notes and accounts receivable + inventories + prepaid expenses
K_f = Fixed Capitals
= Land + buildings + machinery and equipment + deferred charges
F_b = Investor contributions, as a %
d_f = Price deflator

The Taylor-Davis model is not a Total Productivity Model, but rather is a Total Factor Productivity Model.[19] The primary difference between Taylor-Davis' Total Factor Productivity model and a Total Productivity Model is in the method of accounting

[18] Taylor, Davis,: "Corporate Productivity-Getting It All Together", Industrial Engineering, Vol. 9, No. 3, 1977
[19] Sumanth,: "Productivity Engineering and Management", McGraw Hill Book Company, 1987

for raw material. Total Productivity Models include raw material as a straight input, while Total Factor Productivity Models typically include raw materials as components of both inputs and outputs. In the case of the Taylor-Davis Model, the raw material is a component of E (Exclusions) as an output factor and K_w(Working Capital) as an input factor.

2.1.2 Koss and Lewis Model (1993)[20]

Measuring productivity changed from strict Taylorism into a more realistic measurement by including additional factors. Taylorism measures productivity by using tangible factors. *Koss & Lewis*[21], and *Radovilsky and Gotcher*[22] shows that intangible factors can also affect productivity. The new method uses standard measurements, those used in the Taylor model, with the addition of intangible factors that can enhance the accuracy of productivity measurement.

The world market and competition has lead many companies to extend their product requirements from standardized production to a customized process. The need for design quality has become an important issue in order to survive in the highly competitive market. These changes caused the introduction of new productivity attributes such as quality, customer service, worker education, and job satisfaction. These attributes extend the definition of productivity to include culture-specific aspect at the individual, organizational, and social levels of a company. Productivity is therefore not only defined in terms of efficiency, but is also culture-specific. Koss and Lewis proposed the following productivity index:

$$PR = f(X_1, X_2, X_3, \ldots, X_n)$$

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[20] Koss, Lewis: "Productivity or Efficiency – Measuring What We Really Want", National Productivity Review, Spring 1993

[21] Koss, Lewis: "Productivity or Efficiency – Measuring What We Really Want", National Productivity Review, Spring 1993

[22] Radovilski, Gotcher: "Measuring and Improving Productivity: A New Quantitative Approach", Productivity Improvement, May/June 1992

where each X (X_1, X_2, X_i…) represents a series of individual or group of productivity factors, quantitative or qualitative, over a specific time, which are agreed upon by individuals, an organization, or a country as important in determining productivity.[23]

We can then express the productivity function as a productivity index through a mathematical expression as follows

$$PI = \frac{f(X_1) + f(X_2) + f(X_i) + f(X_n)}{n}$$

Where each $f(X_i)$ represents an individual or group productivity factor from the last time (t-1) to this time (t), and n is the total number of group factors.

A group productivity factor $f(X_i)$ can be broken down and expressed as

$$f(X_i) = \frac{W_a X_{ia} + W_b X_{ib} + W_c X_{ic} + \ldots W_y X_{iy}}{(W_a + W_b + W_c + \ldots W_y)y}$$

In this case, each X is an individual productivity factor within the group i. W represents the weighting applied to factor t, and y is the total number of individual factors within the group.

The Koss-Lewis model provides for a high degree in flexibility in that the units for each factor do not have to be in the same terms, a combination of quantitative and qualitative measurements can be used, and factors can be used to express the importance of factors or to provide quality and balance between factors. Some common factors used in the Koss-Lewis model are shown below:

- Labor – Professionals, Managers, Administrative, Production, etc.
- Material – Raw Material, Purchased Parts

[23] Koss, Lewis: "Productivity or Efficiency – Measuring What We Really Want", National Productivity Review, Spring 1993

- Energy – Oil, Gas, Water, Electricity
- Fixed Capital – Land, Buildings, Offices, Machinery and Equipment
- Working Capital – Inventory, Cash, Accounts Receivable
- Sales Revenue, Dividends and Interest
- Customer and Employee Satisfaction
- Quality
- Market Share & Competitive Advantage

2.2 Product Development

2.2.1 Typical Product Development Processes

Developing new products requires numerous tasks and activities performed by people across departments, not strictly within the product development group. These tasks and activities can be grouped into phases based on when they are performed and how they relate to the product development cycle. Typical product development phases include[24]:

- Market Analyses/Product Demand/Business Case
- Product Requirement/Specification/Scope
- Concept Development
- Detailed Engineering & Design
- Analysis, Testing & Design Refinement
- Purchasing & Manufacturing Review & Refinement
- Production
- Marketing
- Product Launch

In new product development three project development processes are most widely used: The Stage-Gate Process, the Spiral Development Process, and the Concurrent

[24] Nepal, Yadav, Solanki: "Improving the NPD Process by Applying Lean Principles: A Case Study", Engineering Management Journal, March 2011

Engineering[25]. Of these, the Stage-Gate Process is most commonly in use among US companies in product development groups[26].

The Stage-Gate process, shown in Figure 2.2.1, is a method in which the main product development tasks are divided into phases such as Product Demand, Product Specifications, Concept Development, Detail Design, Testing & Verification, Manufacturing, and Marketing & Sales. Each phase is executed consecutively and one phase cannot start without the prior phase being completed and a "board" approving the project to move forward to the next stage. This method is commonly used because of the tight control of the process and inherent design reviews within the "gates" between phases. However, this method produces very long cycle times and can be extremely costly due to delays and rework in later phases.

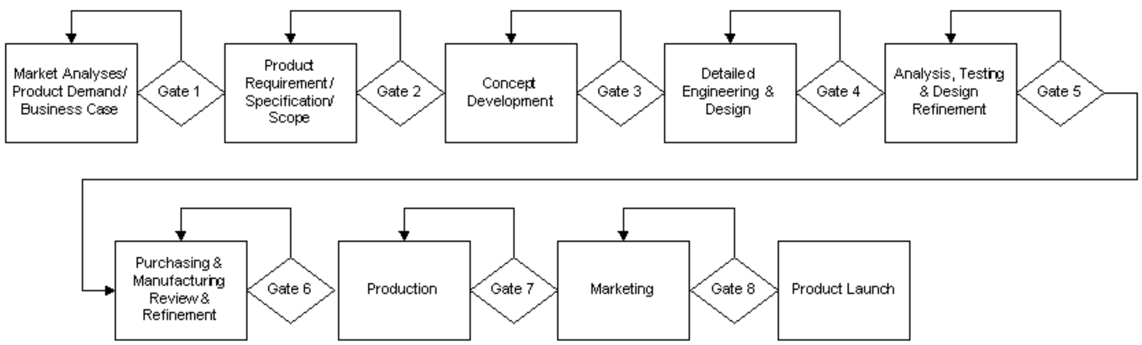

Fig. 2.2.1 Stage-Gate Process Example

As shown in Figure 2.2.2, the Spiral Development Process lends itself to much faster product development times than the Stage-Gate process. In Spiral Development the product goes through a continuous "iterative" loop until release. In this loop the product is designed/built, tested, feedback received, and revised. This continues until the product has met the functional and performance objectives and is released for

[25] Nepal, Yadav, Solanki: "Improving the NPD Process by Applying Lean Principles: A Case Study", Engineering Management Journal, March 2011
[26] Nepal, Yadav, Solanki: "Improving the NPD Process by Applying Lean Principles: A Case Study", Engineering Management Journal, March 2011

production[27]. Although this method improves concept to market time, additional cost is associated with rework from iterative loops.

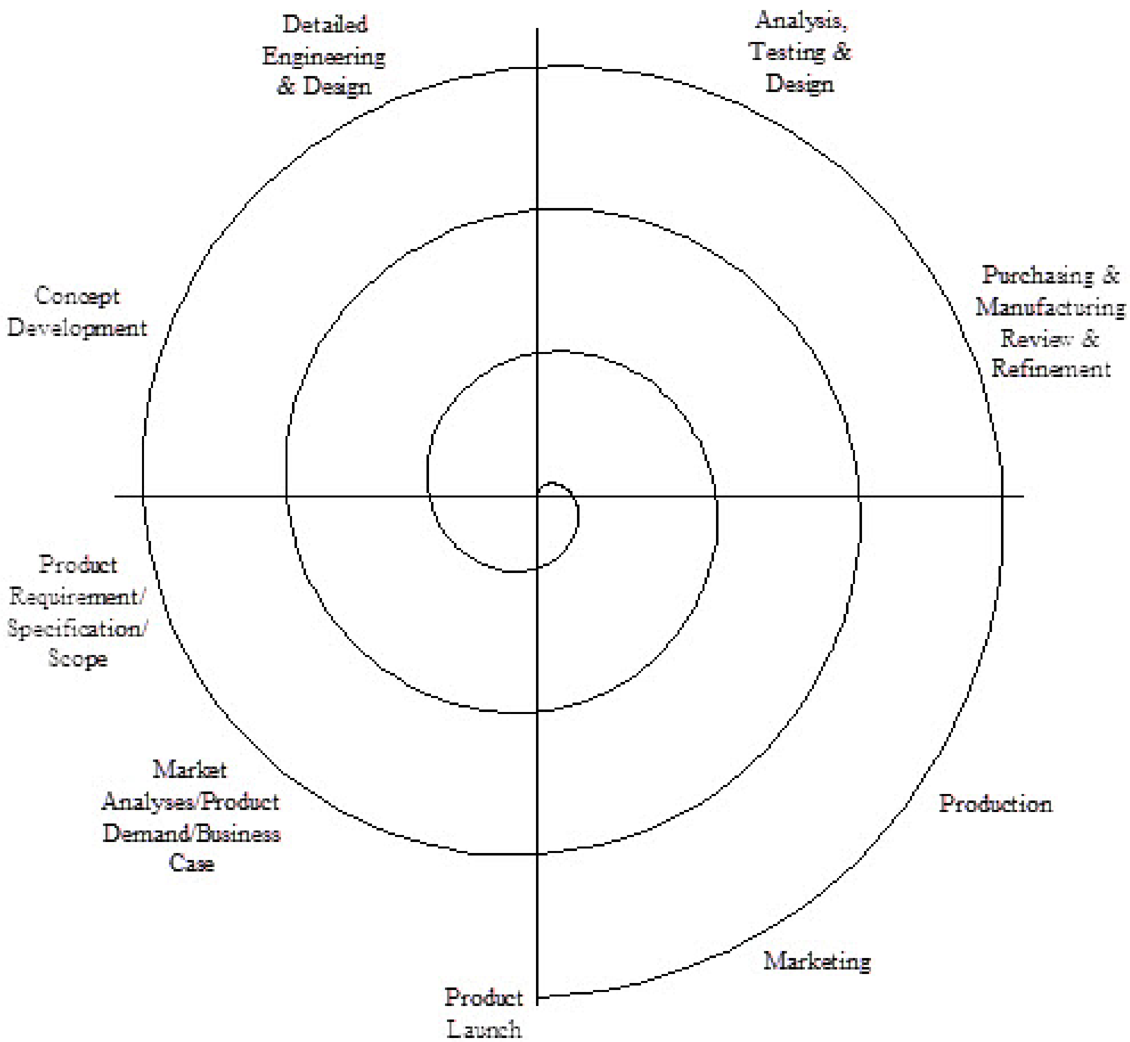

Fig. 2.2.2 Spiral Development Process Example

The third method, Concurrent Engineering, executes many of the phases outlined in the Stage-Gate process simultaneously. Typically, once the Design Specifications are

[27] Nepal, Yadav, Solanki: "Improving the NPD Process by Applying Lean Principles: A Case Study",

identified, Concept Development, Detail Design, Manufacturing, and Marketing and Sales begin working in parallel on the respective phases. A high degree of coordination, communication, and review is required between these cross-functional teams, but this method can lead to decreased development times without incurring significant rework costs[28]. Because of this, Concurrent Engineering is the preferred product development process for companies pursuing lean initiatives. Concurrent Engineering is illustrated in Figure 2.2.3.

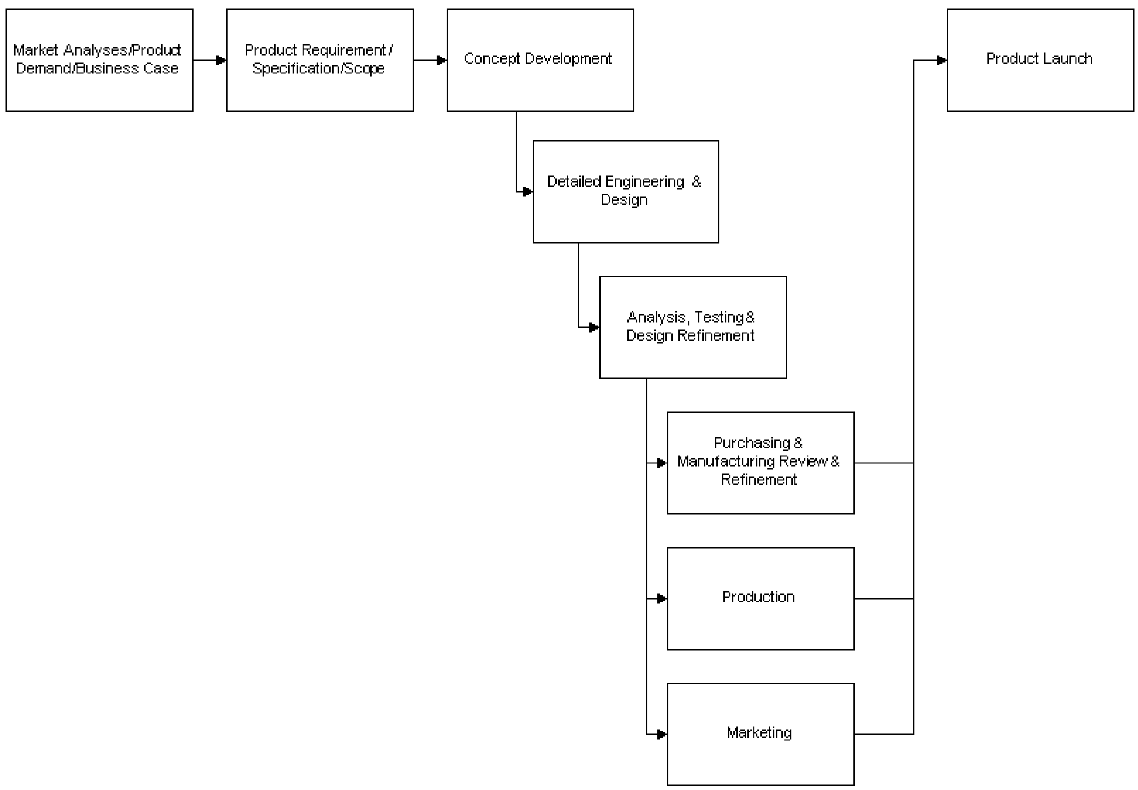

Fig. 2.2.3 Concurrent Engineering Example

Engineering Management Journal, March 2011

[28] Nepal, Yadav, Solanki: "Improving the NPD Process by Applying Lean Principles: A Case Study", Engineering Management Journal, March 2011

2.2.2 Why Product Development Should be Improved

Product development ultimately determines the manufacturing processes to be used in final production as well as the materials used, through the setting of technical and physical specifications. This has a direct impact on the cost, quality, and production lead times of the products produced[29]. In this aspect, Product Design can be improved to reduce manufacturing costs and lead times, as well as improving product quality.

Product development organizations frequently invest large amounts of capital and resources on product development, with development cycles taking many months or years. In some cases the product or technology is obsolete before it comes to market[30]. Lean concepts that are frequently used in production or manufacturing processes can be used in product development processes as well to make efficient use of resources, cut product development time, and thus reduce overall product development costs.

2.2.3 Current Issues Facing Product Development

In today's market, rapid changes in technology and customer demands require products to be developed more quickly than in the past. Over the past 10 years high tech product concept to market times have decreased on average from 2 years to 6 months[31]. The typical Stage-Gate process of product development lends itself to long cycle times due to the asynchronous execution of tasks. Many companies have responded to the demand for shorter lead times by increasing their capital and resources to decrease time in each phase of traditional product development. The most successful organizations have achieved shorter cycle times by becoming more efficient through lean initiatives

[29] Hoppmann, Rebentisch, Dombrowski & Zahn: "A Framework for Organizing Lean Product Development", Engineering Management Journal, March 2011
[30] Wind, Mahand: "Issues and Opportunities in New Product Development: An Introduction to the Special Issue", Journal of Marketing Research, February 1997
[31] Lu, Shen, Ting, Wang: "Research and Development in Productivity Measurement: An Empirical Investigation of the High Technology Industry", African Journal of Business Management, Vol. 4, 2010

such as reducing process waste and changing to a Concurrent Engineering development process.

The global market, with more competition, company downsizing, and lower sales volume for products has placed a high value on reducing product development costs. The cost of developing a product is typically amortized over the sales price of the products with most companies, therefore adding on to the cost of the product. The higher the development cost, the higher the product cost to the consumer. The company with the lowest product development, manufacturing, and material costs will have an edge over the competition in today's "cost conscious" market. In many cases product cost improvement measures take place after product launch where operations, manufacturing, and purchasing seek alternatives to materials, suppliers, and the manufacturing process. This can lead to quality issues and unintended changes in the performance and function of the product. Incorporating supplier integration, process standardization, cross-functional teams, set-based engineering, product variety management, and streamlining the product development process can reduce the up-front product development costs and incorporate product cost reduction before the product is launched[32].

With short product life cycles, due to rapidly changing technology and market demands, quality issues can doom a product. Quality issues, failures, rework, and manufacturing changes after a product has been released can significantly add to the internal costs and prevent a "successful" product from reaching the market before its life cycle is over[33]. It is essential that quality considerations and potential issues be addressed during product development rather than after it's been released. Involving manufacturing, operations, purchasing, and support personnel during product development through concurrent engineering along with developing a system for cross-project knowledge transfer can reduce quality risks. By using proven or standard

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[32] Hoppmann, Rebentisch, Dombrowski & Zahn: "A Framework for Organizing Lean Product Development", Engineering Management Journal, March 2011

[33] Hoppmann, Rebentisch, Dombrowski & Zahn: "A Framework for Organizing Lean Product Development", Engineering Management Journal, March 2011

components/parts, rapid prototyping, simulation, and testing, and set based design practices potential errors and quality issues can be detected and corrected before the product is launched.

Due to the high risk involved and greater expense in development, many companies are reluctant to undertake true new product development. That is, creating an innovative, breakthrough, "new to the market", unique product. Instead, most companies focus on low risk, lower cost, product improvements and product adaptations. While innovative, unique products may carry a lower rate of success, it is these products that have the highest earning potential and can provide a market edge over the competition[34]. A successful product development strategy should include a balance between new products and product enhancements. The high risk of product failures with new products can be mitigated by improvements in selecting which projects are chosen for development. Knowledge-based marketing, consumer modeling, customer/employee involvement, and concept testing are key for selecting the right products to develop and increasing their chances for success.

Aligning new product development with the overall corporate vision, objectives, business model, and strategy is critical for the outputs of a product development group. In many cases product obsolescence, product launch failures, and process failures are a result of not being guided by corporate goals[35]. A new product may be in development for which the market is declining and the corporate strategy is to shift resources to focus in a different area. The corporate vision could see new market opportunities that are untapped, yet there are no products being developed for this. The company could be setting objectives to reduce product material and manufacturing costs, however product development is not making improvements to current products to meet these goals. These

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[34] Wind, Mahand: "Issues and Opportunities in New Product Development: An Introduction to the Special Issue", Journal of Marketing Research, February 1997

[35] Wind, Mahand: "Issues and Opportunities in New Product Development: An Introduction to the Special Issue", Journal of Marketing Research, February 1997

examples highlight the necessity of integrating new product development with the corporate business goals and strategy.

Lean is a production practice focused on eliminating "waste" from the process. By definition, Lean considers any action not adding value to the "product" as wasteful and a target for elimination or improvement in the process. Quite often Six Sigma and Project Management tools are incorporated with lean initiatives as part of the process improvements. Many companies are now instituting Lean Six Sigma and Lean Project Management as part of their process improvements. It is important to note that lean cannot address all issues and challenges that face product development. While the tools and techniques of lean cannot "choose" which projects to undertake, it can improve the process and methods of selecting projects, thus increasing the chances of a project's success. Likewise, lean initiatives cannot forecast what will drive product development, but through process improvements lean can ensure product development is strategically aligned with corporate and market goals to ensure the right products are developed at the right times for the right markets. Lean initiatives have a primary effect on the cost, quality, and delivery time of new product development, but can also have an obvious indirect impact on improving other areas as mentioned above.

2.3 Product Development Improvement Through Lean Initiatives

It is critical to first understand what the potential non-value added activities are in product development and where the "waste can be found. Similar to manufacturing, waste can be found in the following 8 non-value added activities[36].

- Overproduction – Overdesign, or design turnover faster than testing capability
- Defects – Misunderstood or poorly defined customer requirements resulting in unacceptable specifications

[36] Nepal, Yadav, Solanki: "Improving the NPD Process by Applying Lean Principles: A Case Study", Engineering Management Journal, March 2011

- Transportation – Multiple handoffs of information and too many required approvals, multiple locations for designing, prototyping, testing
- Overprocessing – Rework as a result of late problem discovery
- Inventory – Queues of unprocessed information, poor sequencing of tasks
- Unnecessary Movement – Poor data organization, poor office/lab layout
- Waiting – Resource conflicts; late information, hardware, software, poor sequencing
- Underutilization of Staff Knowledge & Skills – Problems not found at the lowest levels; decisions taken without consulting experts; customer and employee feedback ignored

Most often lean is associated with manufacturing and production, but it can be applied to any product, service, or idea that follows a defined process. There are similarities between manufacturing and product development for which lean initiatives can be applied. However, there are numerous differences that should be taken into account as well. These differences are crucial in understanding how to apply lean principles to product development and are outlined below.

First, manufacturing is a repetitive, sequential process. Value is added to the product through repetition, and being sequential the product or work is typically in one place at a time[37]. This limits opportunities for parallel processes. In product development, the work is not repetitive and non-sequential. This allows for parallel processes and additional feedback not available in manufacturing processes.

Manufacturing is bound by fixed requirements. These include design specifications, quality, and production times. Product development is not bound by these, but is responsible for setting them. Therefore, product development must be flexible to change or adapt to new information and decide what is acceptable based on time, cost, and value.

Lastly, evaluating and taking risks in product development is essential in developing new technologies and products. Taking high risks in manufacturing is not typically justified as it can cause quality issues, production loss, and production delays.

A number of studies have found that six major lean principles are common among companies streamlining their product development: concurrent engineering, strong project management, communication, process flow, teamwork, and supplier involvement. Toyota's Product Development System, from which lean is derived, currently identifies 13 principles, grouped into three categories: people, process, and technology. A recent study by Hoppman, Rebentisch, Dombrowski, and Zahn compiled research and data from the past two decades defining 11 core components of lean product development[38]. It is these 11 principles that will be explored further as methods for improving product development through lean.

Strong Project Manager – It is not uncommon for product development to have project managers overseeing the project. However, the role and responsibilities of the project manager are crucial in a lean environment. Not only must the project manager be accountable for the project schedule and cost, but also the performance targets. At the beginning of the project the project manager must research and analyze customer requirements and competitors products and translate them into functional requirements and goals for the project team. The project manager should be the most experienced and technically knowledgeable engineer on the team as well as being able to manage the schedule, cost, and performance metrics.

Specialist Career Path – In traditional organizations, engineers typically do not spend a lengthy period of time in the same functional area. Rapid career path development and promotion often emphasize general management and administrative

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[37] Reinertsen, Shaeffer: "Making R&D Lean", Research Technology Management, July/August 2005

tasks over technical skills. This frequently leaves gaps in technical knowledge and skills as a result of turnover and underdeveloped engineering skills in product development. Lean encourages specialist career paths where the development of technical expertise and long term team building is promoted.

Workload Leveling – An unbalanced workflow directly relates to the quality, lead time, and costs of product development, as well as resource utilization. Reliable and effective methods for planning and monitoring shared resources across product development projects are critical. Multi-project management, supported by project level capacity planning and scheduling are some of the tools that can aid in workload leveling. Because of the dynamic and sometimes unpredictable nature of product development, flexibility to increase or decrease resource capacity is important. An effective lean process will consider these factors and have a plan for quick response.

Responsibility-Based Planning and Control – Lean Product Development supports the use of Responsibility-Based planning versus the traditional Top-Down planning approach. In Responsibility-Based planning the project manager only sets the major project milestones for the project. The engineer is then responsible for breaking down their own tasks, determining the start points, durations, etc. This method provides for more ownership and individual responsibility over their tasks and allows freedom to explore new approaches as long as milestones are met.

Cross-Project Knowledge Transfer – Often times mistakes are repeated or similar problems are encountered and solved again on products/projects. It is essential to build upon past knowledge to improve quality and reduce wasted time. There are numerous methods for capturing and reviewing corporate knowledge, some of which are listed below:

- Corporate/Department Best Practices Handbook

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[38] Hoppmann, Rebentisch, Dombrowski & Zahn: "A Framework for Organizing Lean Product Development", Engineering Management Journal, March 2011

- Past Project Lessons Learned Notes
- Product/Project Issue Database
- Past Project/Product Designs
- Standards & Checklists

At a minimum data and records should be reviewed at the beginning of product development, at major milestones, and when a new design task is started.

Simultaneous/Concurrent Engineering – Unlike traditional Stage-gate product development, where each phase of product development is completed before moving to the next phase, concurrent product development allows for overlapping development and in some cases complete simultaneous development of phases. This does require strong coordination between cross-functional teams such as product development, marketing, manufacturing, purchasing, and quality. In this environment all team members must be actively involved in design reviews and information sharing from project onset. This is a major change from traditional product development where many team members are not involved until their phase begins. Concurrent engineering can be difficult to implement if there is not a clear communication plan and all stakeholders are not actively involved at the beginning of the project, however this does provide the quickest returns on shortening product development cycle times.

Supplier Integration – An effective way to solve design issues, lower manufacturing costs, and identify potential quality risks is to involve part/material suppliers during product development. Their specialized knowledge and expertise can save both time and money as well as help build and maintain a working relationship.

Product Variety Management – Lean product development experts promote three methods for managing product variety. First, when a part can be easily ordered from a stock supplier and there is no cost advantage to produce it in house, it is recommended to do so. It would be considered a “waste” to spend resources to develop and produce something in house that can be purchased from a vendor who already has the knowledge and experience. Second, a company should try to reuse parts from previous versions, different products, or different product families. A new part should only be developed if there is end user value added to it. Lastly, products should be divided into subassemblies or modules where these subassemblies or modules can be used across different products or product lines.

Rapid Prototyping, Simulation & Testing – Based on the large number of design iterations common with product development, identifying and solving problems quickly is essential in decreasing the time to market and improving overall product quality and functionality. Technologies and methods for quickly evaluating designs and providing feedback to the development team are a critical lean tool for product development. Low cost prototypes in the concept phase, progressing to more complex and complete prototypes throughout the design phase can be one method. The use of 3-D modeling, computer simulation, and digital assembly are other tools that can aid in this area.

Process Standardization – The most critical principle in any lean implementation, whether it's product development, manufacturing, service, or any other organization is Process Standardization and Optimization. Although product development projects can be unique, most individual tasks for planning and executing these projects are repetitive and similar from project to project. Standardizing and optimizing these tasks increases product development performance by increasing efficiency, reducing waste, reducing process task variability, minimizing errors, collecting and using knowledge, and serves as a base for continuous improvement. Developing and defining a standard process for product development is instrumental in improving overall efficiency. By creating a "road map" of the process each step in the product development can be defined and documented with instructions, checklists, reviews, work procedures, etc. With this tool each product development project can be executed in the same way each time, all team members will know what to do, when to do it, why to do it, and how to do it. By incorporating process standardization, lean tools such as Value Stream Mapping can be used to identify waste and further improve efficiency. Value Stream Mapping is a continuous improvement tool which identifies non-value added steps in the process and removes or reorganizes the process to make it more efficient. Several other tools and techniques such as Design Structure Matrix (DSM), Cause and Effect Matrix, 5 Whys, Root Cause Analysis, and Project Management are often implemented in process standardization to improve quality, reduce cost, and improve efficiency.

Set-Based Engineering – In typical product development a small number of alternate concepts are developed at the beginning of the project. The "closest fit" concept is then chosen, and throughout the design and development cycle this concept is refined and redesigned to meet the specifications until it becomes the final product. This can significantly increase product development costs as changes late in the cycle can cause disruptions in workflow, redesign of multiple components, and affect final manufacturing. Set-based engineering promotes the development of a large number of alternate concepts at the project start. Each concept is tested and analyzed in parallel and is not eliminated until it is proven to be inferior to other designs. The set of concepts is narrowed down until a single unchanged original concept remains, which then goes into production. This method has proven to be more cost effective than the traditional product development method.

The main goal of applying lean tools to product development is to decrease the "concept to release" time, while improving quality, and reducing cost (primarily through labor resource reduction). Some of the common objectives of improving product development through lean initiatives are[39]:

- Reducing the product development cycle time
- Improving product development capability and capacity
- Increasing the number of ideas/products with high market share and payback potential
- Increasing the number of products launched per year

[39] Nepal, Yadav, Solank: "Improving the NPD Process by Applying Lean Principles: A Case Study", Engineering Management Journal, March 2011

- Improving the quality of new products by reducing the number of defects and warranty
- Creating product development standards and processes

Companies typically begin their lean initiative process by first identifying the problems, or gaps in the current process. This is done by forming a “task force” to develop a value-stream map of the current process, identifying value added versus non-value added activities, and analyzing past projects for adherence/validation to the value-stream map. Often, benchmarking against optimal objectives, or a known competitors metrics can aid in identifying the problem areas and gaps. The team members then agree on what activities are non-value added, what must change in the product development process, methods, and organization, and establish current and future performance targets. The task force can then set clear goals and objectives for the lean initiative, generate a project plan, and gather support from company leaders and stakeholders.

The next step is to perform an in depth analysis on the non-value added activities to understand their nature and root causes. This is necessary so the process can be modified with integrity. The in depth analysis is done through interviews with subject matter/process experts, Design Structure Matrix (DSM) analysis, root cause analysis, cause and effect matrix, 5 whys, and other similar tools. It is critical to understand why each non-value added activity is currently being performed and how it was incorporated into the process to begin with. Only by understanding this can it be effectively removed and the process redefined to work smoothly without the step.

The third step is to create a new product development value stream map which removes the non-value added activities and incorporates the process, method, and organizational changes identified in the first section. This can be very time consuming and may take many iterations before everything flows and all stakeholders are in agreement with the process and order. In creating the new value stream map, is it critical to create parallel and non-dependent tasks where possible to prevent waste from waiting and improve overall cycle time and efficiency.

The fourth and most difficult step is implementation. Once the new value stream map is defined and all stakeholders are in consensus new procedures, checklists, and documents. should be developed and employees trained to ensure the process is adhered to. Changing the process from how “we used to do it” to “how we are going to do it” requires support and teamwork from everyone involved in the process to make it successful. A clear understanding of the goals and objectives, a path for implementation, active involvement from management, and supporting documentation and training are all necessary for successful implementation. The final step is continuous improvement. Lean never ends. The value stream map should be reviewed on a regular basis for process improvements, and everyone should always look for “waste” that can be removed from the process. At least annually company/department goals should be reviewed to make sure they are being met, or if the goals are obsolete and need to be adjusted. If the goals are obsolete, then the lean process should be reviewed for improvements.

3.0 Methodology

The goal of this project was to effectively model productivity within a new product development environment and illustrate the impacts of lean initiatives. The purpose of the methodology is to underline the main steps implemented to complete this project. The steps are listed as different sections and explained to justify their usage.

3.1 Background Research

The first step in developing an effective productivity model was to research material and topics relevant to the study of productivity in relation to new product development. We began by analyzing, summarizing, and categorizing the many definitions of productivity. Our next step was to research and collect data on previous productivity models, from early models of the 1920's to the most recent. We then studied research, previous productivity cases, and data from product development business units to determine which input and output factors are essential for use in a productivity model in analyzing performance trends. From this information we could then list the factors to be used within the model and select the type of productivity model best suited for the new product development application.

3.2 Defining and Measuring Productivity Attributes

In order to develop a successful productivity model, a list of factors must be developed, both quantitative and qualitative, that contribute to the competitiveness of an organization. Then, the attributes must be defined by assigning metrics; which provide a means to "measure" the attribute. Once all the metrics have been established, a system of weights for each attribute and metric may need to be calculated in order to obtain a mathematically balanced model.

Through research seven key productivity factor groups which should be used for measuring productivity in product development were identified:

L – Labor

Q – Quality

C_w – Working Capital

C_f – Fixed Capital

R – Revenue

V – Added Value

M – Miscellaneous

Within these seven groups we selected multiple individual productivity factors as shown in Figure 3.2.1. Each factor below is shown with the units they are measured in by their associated metrics or Key Performance Indicators (KPIs).

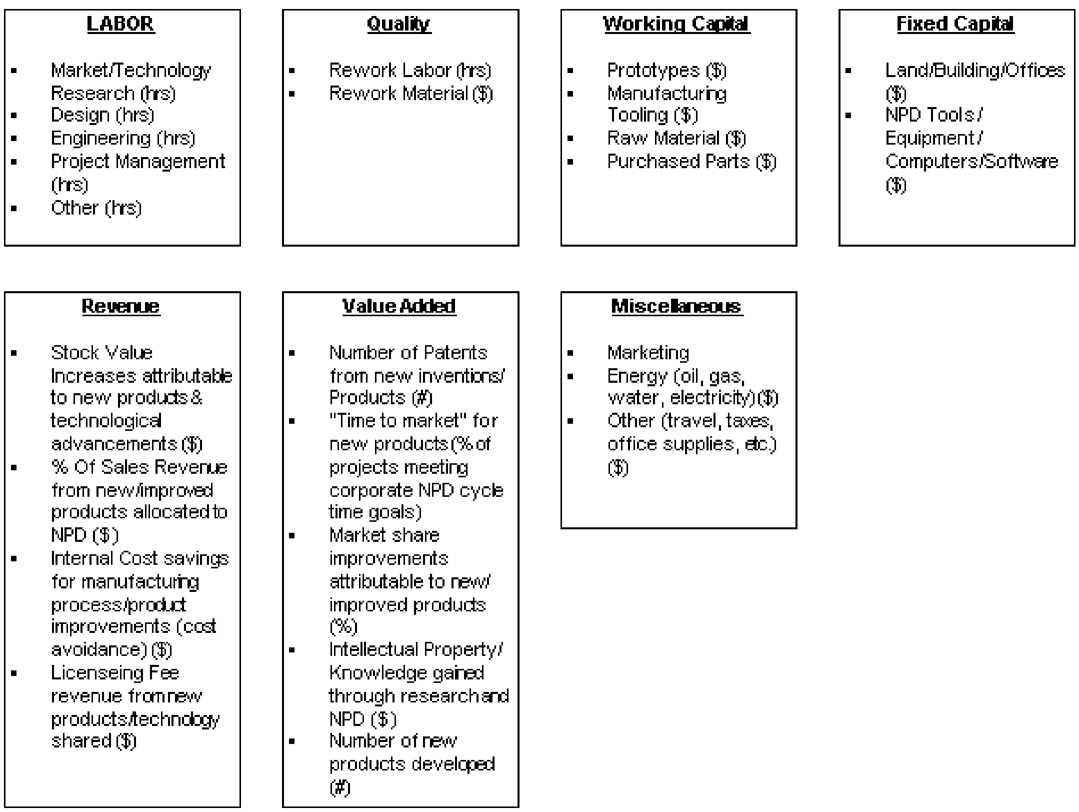

Fig. 3.2.1 Factors for Product Development Productivity Model

Once we identified the factors to be used in the productivity model it was necessary to determine if any weighting (scaling) was required to achieve balance within the model. To determine weights, we had to analyze each productivity group individually and independently, as the weights are applied to individual factors and only affect the group calculation. In groups where the units are the same and the expected range in values does not exceed a factor of 10 no weighting was necessary. For cases not meeting this requirement the factors were weighted so that no factors had a more significant impact on the productivity calculation than other factors. Figure 3.2.2 summarizes the weights used for each factor.

Individual Factors - Labor	**Weight**
Market/Technology Research (hrs)	1
Design (hrs)	1
Engineering (hrs)	1
Project Management (hrs)	1
Other (hrs)	1
Individual Factors - Quality	**Weight**
Rework Labor (hrs)	1
Rework Material ($/1000)	1
Individual Factors - Working Capital	**Weight**
Prototyping ($/1000)	1
Manufacturing Tooling ($/1000)	1
Raw Material ($/1000)	1
Purchased Parts ($/1000)	1
Individual Factors - Fixed Capital	**Weight**
Land/Building/Offices ($/1000)	1
NPD Tools/Equipment/Computers/Software ($/1000)	1
Individual Factors - Revenue	**Weight**
Stock Value Increases attributable to new products & technological advancements ($/1000)	0.934
% Of Sales Revenue from new/improved products allocated to NPD ($/1000)	1
Internal Cost savings for manufacturing process/product improvements (cost avoidance) ($/1000)	0.762
Licensing Fee revenue from new products/technology shared ($/1000)	1.111
Individual Factors - Value Added	**Weight**
# of Patents from new inventions/Products (#)	0.8
"Time to market" for new products - % of projects meeting corporate NPD cycle time goals (%)	1.185
Market share improvements attributable to new/improved products (%)	0.8
Value of Intellectual Property/Knowledge gained through research and NPD ($/1000)	1
# of new products developed (#)	0.889
Individual Factors - Miscellaneous	**Weight**
Marketing ($/1000)	1
Energy ($/1000)	1
Other (travel, taxes, office supplies, etc) ($/1000)	1

Fig. 3.2.2 Weights Used for Factors

3.3 Productivity Model

As described in Chapter 2, there are no standards, preferred models, or established processes for choosing which productivity model should be used for a given application. Model selection is purely user driven based on the type of inputs/outputs, the available data, measurement objectives, level of detail required, and the amount of time and resources available to develop the model. A few productivity experts have claimed that non-parametric frontier based models, with their Data Envelopment Analysis (DEA) approach would be the best models for measuring productivity in R&D and Product Development. They justify this by the potentially large number of complex inputs and outputs, many of which are qualitative rather than quantitative. Because the data required for these types of models is not readily available, and they are complex to develop, most of this work is theoretical and has little real world application to date. The most successful and in-depth studies on productivity in R&D and Product Development, utilize a non-frontier parametric model, specifically the Cobb-Douglas model[40]. This model was chosen for its simplistic approach, ease of development, and the limited amount of available data which dictated the inputs and outputs. For the same reasons, and the proven success of using non-frontier parametric models for measuring productivity in Product Development a similar approach will be used for this study. A slightly more modern method, the Koss-Lewis model has been selected for its flexibility in accounting for some qualitative inputs and outputs and the ability to weight factors to achieve model balance.

3.4 Lean Implementation

In conjunction with developing a model for analyzing productivity in product development, we also applied lean principles to new product development as a method for increasing productivity. We first researched the basic principles, theories, and applications of lean. Next, we researched the recent history, case studies, and company profiles for successful implementation of lean initiatives within a product development

[40] Griliches: "R&D and Productivity: The Econometric Evidence", University of Chicago Press, 1998

business unit. This research allowed several lean initiatives to be selected as part of a case study to determine their impacts on productivity within new product development. Several lean initiatives relevant to product development were included, specifically Strong Project Manager, Specialist Career Path, Workload Leveling, Responsibility-Based Planning & Control, Cross-Project Knowledge Transfer, Simultaneous/Concurrent Engineering, Supplier Integration, Product Variety Management, Rapid Prototyping, Simulation & Testing, Process Standardization, and Set-Based Engineering. Using the productivity model we developed we were able to demonstrate the productivity effects of implementing lean initiatives in product development, and the value of such analysis in measuring the impacts of lean implementation.

4.0 The Effect of Lean Initiatives on Product Development Productivity

In this section we will illustrate how productivity models can capture improvements due to lean, through initiatives that impact cost, quality, and cycle time. The following eleven principles were previously identified as methods for improving product development:

- Strong Project Manager
- Specialist Career Path
- Workload Leveling
- Responsibility-Based Planning and Control
- Cross-Project Knowledge Transfer
- Simultaneous/Concurrent Engineering
- Supplier Integration
- Product Variety Management
- Rapid Prototyping, Simulation and Testing
- Process Standardization
- Set-Based Engineering

These lean principles we will use to illustrate the positive effects on productivity in product development.

To begin the chapter the productivity model we created is first described.

4.1 Productivity Model

The complete productivity index from the Koss Lewis model can be expressed as follows:

$$PI = \frac{f(X_1) + f(X_2) + f(X_i) + f(X_n)}{n}$$

Where each individual group productivity factor can be expressed in the form of

$$f(X_i) = \frac{W_a X_{ia} + W_b X_{ib} + W_c X_{ic} + \ldots W_y X_{iy}}{(W_a + W_b + W_c + \ldots W_y) y}$$

Each $X_{ij,}$ j = a . . . y, X is then calculated as X_{ij} (t)/ X_{ij} (t-1) in cases where an increase in the measure indicates a positive effect on productivity, or X_{ij} (t-1)/ X_{ij} (t) where a decrease in the value signifies a positive effect on productivity. X_{ij} (t) would be the measured value of the current period, while X_{ij} (t-1) is the value of the previous period.

By substituting the seven group productivity factors identified in Section 3.2 into the productivity index expression we can indentify the final product development model as follows:

$$PI = \frac{f(L) + f(Q) + f(C_w) + f(C_f) + f(R) + f(V) + f(M)}{7}$$

In figure 3.2.1 we identified the individual factors within the seven groups making up the productivity index expression. From this, the group productivity factor functions can be derived according to the following equations.

$$f(L) = \frac{W_1 L_1 + W_2 L_2 + W_3 L_3 + W_4 L_4 + W_5 L_5}{(W_1 + W_2 + W_3 + W_4 + W_5)5}$$

$$f(Q) = \frac{W_2 Q_2 + W_2 Q_2}{(W_1 + W_2)2}$$

$$f(C_w) = \frac{W_1 C_{w1} + W_2 C_{w2} + W_3 C_{w3} + W_4 C_{w4}}{(W_1 + W_2 + W_3 + W_4)4}$$

$$f(C_f) = \frac{W_1 C_{f1} + W_2 C_{f2}}{(W_1 + W_2)2}$$

$$f(R) = \frac{W_1R_1 + W_2R_2 + W_3R_3 + W_4R_4}{(W_1 + W_2 + W_3 + W_4)4}$$

$$f(V) = \frac{W_1V_1 + W_2V_2 + W_3V_3 + W_4V_4 + W_5V_5}{(W_1 + W_2 + W_3 + W_4 + W_5)5}$$

$$f(M) = \frac{W_1M_1 + W_2M_2 + W_3M_3}{(W_1 + W_2 + W_3)3}$$

with these eight equations we can successfully measure productivity in product development, using a Koss-Lewis based model.

4.2 Case Study and Baseline Analysis

To apply the productivity model to a case study, it is first necessary to establish the company profile, baseline data set, and baseline productivity factor and index values. The company selected is a hypothetical mid-sized high tech manufacturing firm with annual sales revenue of $500M and a total of 20 full time product development employees. We created a data that included values for the individual and group productivity factors identified in Figure 3.2.1, which are explained in detail below. The baseline data set and values were based on my professional experience as a Product Manager and Engineering Manager, overseeing product development for a smaller organization. The data was extrapolated to fit a larger company and any unavailable values estimated based on similar data. These baseline values are before the implementation of any lean initiatives. For comparative purposes, the baseline data from one period (year) to the next remained unchanged.

All factors within this group have the units expressed as the total number of hours spent for the period (in this case one year). The Market/Technology Research, Design, Engineering, and Project Management are based on the 20 full time product development employees with the following breakdown of time spent per activity; Market/Technology Research: 15%, Design: 40%, Engineering: 35%, Project Management: 10%. The Other labor hours is attributable to resources outside of product development and is based on 30 employees spending 10% of their time in direct support of product development. Table 4.2.1 provides the baseline data for the labor group.

Individual Factors - Labor	Weight	Baseline
Market/Technology Research (hrs)	1	6120
Design (hrs)	1	16320
Engineering (hrs)	1	14280
Project Management (hrs)	1	4080
Other (hrs)	1	6120

Table 4.2.1 – Baseline Labor Group Productivity Factor Values

Using the expression for the Labor group productivity factor and the baseline value for time period 1 and time period 2 we can establish a baseline productivity factor value:

$$f(\mathrm{L}) = \frac{1(6{,}120/6{,}120) + 1(16{,}320/16{,}320) + 1(14{,}280/14{,}280) + 1(4{,}080/4{,}080) + 1(6{,}120/6{,}120)}{(1+1+1+1+1)5} = 0.2$$

Based on this, a productivity factor value >0.2 indicates an improvement in productivity for the labor factor. Conversely, a productivity factor value <0.2 indicates a decrease in productivity.

In the Quality group productivity factor, the Rework Material is expressed as the total cost in dollars for the material used divided by 1000. In this case, 5625 equals $5.625M and was based on 10% of the cost of goods sold (COGS) attributable to product development. Rework Labor is the total number of hours for all company employees spent correcting quality/rework issues related to product development during the given time period (1 year). Table 4.2.2 provides the baseline data for the quality group

Individual Factors - Quality	Weight	Baseline
Rework Labor (hrs)	1	29300
Rework Material ($/1000)	1	5625

Table 4.2.2 – Baseline Quality Group Productivity Factor Values

Inserting these values into the expression for the Quality group productivity factor we can see that the baseline value would be 0.5, thus a productivity value >0.5 for future periods would indicate an improvement in productivity in this area. The equation is shown below:

$$f(Q) = \frac{1(29{,}300/29{,}300) + 1(5{,}625/5{,}625)}{(1+1)2} = 0.5$$

All individual factors within the Working Capital group are based on actual dollars spent in support of product development (including product launch and beta releases) during the one year time period. The values are expressed as cost in dollars divided by 1000. Table 4.2.3 provides the baseline data for the working capital group.

Individual Factors - Working Capital	Weight	Baseline
Prototyping ($/1000)	1	350
Manufacturing Tooling ($/1000)	1	1600
Raw Material ($/1000)	1	1800
Purchased Parts ($/1000)	1	1250

Table 4.2.3 – Baseline Working Capital Group Productivity Factor Values

Using the Working Capital group productivity equation we can see that the baseline value would equal 0.25, as shown below:

$$f(C_w) = \frac{1(350/350) + 1(1{,}600/1{,}600) + 1(1{,}800/1{,}800) + 1(1{,}250/1{,}250)}{(1+1+1+1)4} = 0.25$$

Future period values less than 0.25 would indicate a decrease in productivity, while values greater than 0.25 would indicate and increase in productivity.

Similar to the Working Capital group, the Fixed Capital group individual factors are actual costs incurred over the one year time period to directly support product development. These values are expressed as cost in dollars divided by 1000 as well. The baseline values for the fixed capital group are provided in Table 4.2.4

Individual Factors - Fixed Capital	Weight	Baseline
Land/Building/Offices ($/1000)	1	1750
NPD Tools/Equipment/Computers/Software ($/1000)	1	750

Table 4.2.4 – Baseline Fixed Capital Group Productivity Factor Values

From the expression for the Fixed Capital group productivity we can see that the baseline value is 0.5 and values greater than that indicate increases in productivity:

$$f\,(C_f) = \frac{1(1{,}750/1{,}750) + 1(750/750)}{(1+1\,)2} = 0.5$$

The Stock Value is based on the annual increase in value (expressed as dollars divided by 1000) which can be attributed to new products and advances in technology through R&D. In this baseline there was a 3% increase in stock value, 35% of which was attributed to product development/R&D, which resulted in a value of $5.25M. Fifteen percent of the company's annual revenue of $500M was a direct result of new/improved products developed that year. Based on this, $75M (75000) was used as the baseline for percent of sales revenue from new/improved products allocated to NPD. Direct revenue from technology or products sold off or leased to other companies that were developed during the current period are measured as dollars divided by 1000 and are captured under licensing fee revenue from new products/technology shared. The internal cost savings through product/process improvements is measured as dollars saved divided by 1000.

Within the Revenue productivity group, the individual factors must be weighted in order to balance the model and prevent one factor from increasing the productivity by a greater amount than another factor. The requirement for weighting the factors is due to the wide range in values between the four factors. The weights were calculated based on the period A versus baseline date for each factor in relation to the other factors within the groups. The weights were calculated so that each individual factor within the group would be equal when the productivity was calculated. Table 4.2.5 provides the baseline values and weights for the revenue group.

Individual Factors - Revenue	Weight	Baseline
Stock Value Increases attributable to new products & technological advancements ($/1000)	0.934	5250
% Of Sales Revenue from new/improved products allocated to NPD ($/1000)	1	75000
Internal Cost savings for manufacturing process/product improvements (cost avoidance) ($/1000)	0.762	200
Licensing Fee revenue from new products/technology shared ($/1000)	1.111	12500

Table 4.2.5 – Baseline Revenue Group Productivity Factor Values

Using the expression for the Revenue group productivity factor and inserting the individual baseline values we can calculate the group productivity factor baseline.

$$f(\text{R}) = \frac{0.934(5{,}250/5{,}250) + 1(75{,}000/75{,}000) + 0.762(200/200) + 1.111(12{,}500/12{,}500)}{(0.934 + 1 + 0.762 + 1.111)4} = 0.25$$

Productivity gains within this group would result from values greater than 0.25.

The Value Added group contains some units/measures that are quite different from the hours and dollars we have seen thus far as factors. Several factors within this group are more qualitative than quantitative and cannot be directly measured by labor, cost, or revenue. Because of this, the factors are represented using units based on their measurable form. The Number of Patents from new inventions/products is measured as number of new patents filed, and the Number of new products developed is measured as the number of units produced over the one year period. The Time to Market for new products can be measured by the percent of NPD projects meeting the corporate cycle time goals, in this case 8 months. The value of the company's intellectual property is estimated here as 45% of the annual sales revenue attributed to product development and is expressed as dollars divided by 1000. Due to the difference in units and the range of values between the individual factors it is necessary to weight the factors accordingly so that the model achieves balance. The baseline values and weights for the value added group are provided in Table 4.2.6

Individual Factors - Value Added	Weight	Baseline
# of Patents from new inventions/Products (#)	0.8	3
"Time to market" for new products - % of projects meeting corporate NPD cycle time goals (%)	1.185	80.00%
Market share improvements attributable to new/improved products (%)	0.8	3.00%
Value of Intellectual Property/Knowledge gained through research and NPD ($/1000)	1	33750
# of new products developed (#)	0.889	4

Table 4.2.6 – Baseline Value Added Group Productivity Factor Values

Inserting these values into the expression for the Value Added group productivity factor we see that the baseline value would be 0.2:

$$f\,(\mathrm{V}) = \frac{0.8(3/3) + 1.185(80/80) + 0.8(3/3) + 1(33{,}750\,/\,33{,}750) + 0.889(4\,/\,4)}{(0.8 + 1.185 + 0.8 + 1 + 0.889)5} = 0.2$$

A productivity value >0.2 for future periods would indicate an improvement in productivity in this area.

The Miscellaneous group individual factors are actual costs incurred over the one year time period to directly support product development. These values are expressed as cost in dollars divided by 1000. Table 4.2.7 provides the baseline values for the miscellaneous group.

Individual Factors - Miscellaneous	Weight	Baseline
Marketing ($/1000)	1	125
Energy ($/1000)	1	200
Other (travel, taxes, office supplies, etc) ($/1000)	1	235

Table 4.2.7 – Baseline Miscellaneous Group Productivity Factor Values

Using the expression for the Miscellaneous group productivity factor and the baseline values for both periods we can establish a baseline productivity factor value as follows.

$$f\,(\mathrm{M}) = \frac{1(125/125) + 1(200/200) + 1(235/235)}{(1+1+1\,)3} = 0.333$$

The baseline value for the Miscellaneous group productivity factor is 0.333, therefore values greater than this signify an increase in productivity in this area.

Given the baseline values known for each group productivity factor, we can calculate the overall baseline productivity index:

$$\mathrm{PI} = \frac{0.2 + 0.5 + 0.25 + 0.5 + 0.25 + 0.2 + 0.333}{7} = 0.319$$

We can now see that the baseline productivity index for this analysis is 0.319. Productivity index values for future periods which exceed 0.319 suggest an overall increase in productivity, while values less than 0.319 would reveal a decrease in productivity.

4.3 Lean Initiative Analysis

With the objective of increasing productivity within product development, we assume the case study company formed a “task force” to analyze the current process to identify the problem areas and gaps, using a typical four-step lean implementation process[41]. Through value stream mapping (VSM) and analyzing past projects the task force agreed on which activities are non-value added, what must change in the product development process, methods, and organization, and established performance targets. Through its analysis the company established the following goals.

- Meet the product development cycle time of 8 months for at least 95% of projects
- Increase the number of new products developed per year by 25%
- Improve the quality of new products by decreasing rework costs
- Increase the number of products with high market share and payback potential
- Develop system standards and processes

The task force then performed an in-depth analysis of the current process, desired changes, and process waste. Subject matter experts within the organization were called upon to share their knowledge, ideas, and inputs. Root cause analysis, cause and effect matrices, 5 Whys, and other tools were also used to gain a clear understanding of all activities before processes were modified and lean initiatives implements.

The next step involved creating a new process map incorporating the lean initiatives, process, method, and organizational changes, as well as removing non-value added activities. Several revisions to the new process map were required until all process stakeholders were in agreement, the new process supported the goals set in the first step, and the process map flowed smoothly with no foreseeable problem areas or gaps.

The fourth step was to implement the new process map and all associated changes. Support and teamwork was required from all aspects of the company including management, product development, and manufacturing. New procedures, documents, and checklists had to be developed and everyone involved in the processes had to be

[41] Nepal, Yadav, Solanki: "Improving the NPD Process by Applying Lean Principles: A Case Study", Engineering Management Journal, March 2011

trained. It was critical to convey the goals and objectives, and the path for implementation to make this project a success.

After one year, data was collected and measured against the previous baseline to evaluate the effects of the lean initiatives on productivity and determine if the initial goals had been met. During this period the company's annual sales revenue stayed at $500M and the total full time product development employees remained at 20 from the previous period. The results are discussed below, specifically illustrating how certain lean initiatives affected the productivity factors.

Table 4.3.1 presents the productivity factors at baseline and period A, one year after baseline. The values in period A reflect the lean initiative implementation. As in the baseline analysis the productivity factor for each group can be calculated according to their respective expressions using the Period A data compared with the baseline data. In cases where an increase in the value indicates an improvement or positive indication the formula is expressed as Period A/Baseline. Where a decrease of the measure indicates an improvement the formula is expressed as Baseline/Period A. Using the correct expression for normal or inverse is important to correctly measure the increase in productivity for the factors.

Individual Factors - Labor	Weight	Baseline	Period A
Market/Technology Research (hrs)	1	6120	6120
Design (hrs)	1	16320	16320
Engineering (hrs)	1	14280	14280
Project Management (hrs)	1	4080	4080
Other (hrs)	1	6120	6120
Labor ƒ(L)		**0.200**	**0.200**
Individual Factors - Quality	**Weight**	**Baseline**	**Period A**
Rework Labor (hrs)	1	29300	23437.5
Rework Material ($/1000)	1	5625	4500
Quality ƒ(Q)		**0.500**	**0.625**
Individual Factors - Working Capital	**Weight**	**Baseline**	**Period A**
Prototyping ($/1000)	1	350	350
Manufacturing Tooling ($/1000)	1	1600	1600
Raw Material ($/1000)	1	1800	1800
Purchased Parts ($/1000)	1	1250	1250
Working Capital ƒ(Cw)		**0.250**	**0.250**
Individual Factors - Fixed Capital	**Weight**	**Baseline**	**Period A**
Land/Building/Offices ($/1000)	1	1750	1750
NPD Tools/Equipment/Computers/Software ($/1000)	1	750	750
Fixed Capital ƒ(Cf)		**0.500**	**0.500**
Individual Factors - Revenue	**Weight**	**Baseline**	**Period A**
Stock Value Increases attributable to new products & technological advancements ($/1000)	0.934	5250	7500
% Of Sales Revenue from new/improved products allocated to NPD ($/1000)	1	75000	100000
Internal Cost savings for manufacturing process/product improvements (cost avoidance) ($/1000)	0.762	200	350
Licensing Fee revenue from new products/technology shared ($/1000)	1.111	12500	15000
Revenue ƒ(R)		**0.250**	**0.350**
Individual Factors - Value Added	**Weight**	**Baseline**	**Period A**
# of Patents from new inventions/Products (#)	0.8	3	5
"Time to market" for new products - % of projects meeting corporate NPD cycle time goals (%)	1.185	80.00%	90.00%
Market share improvements attributable to new/improved products (%)	0.8	3.00%	5.00%
Value of Intellectual Property/Knowledge gained through research and NPD ($/1000)	1	33750	45000
# of new products developed (#)	0.889	4	6
Value Added ƒ(V)		**0.200**	**0.285**
Individual Factors - Miscellaneous	**Weight**	**Baseline**	**Period A**
Marketing ($/1000)	1	125	125
Energy ($/1000)	1	200	200
Other (travel, taxes, office supplies, etc) ($/1000)	1	235	235
Miscellaneous ƒ(M)		**0.333**	**0.333**

Table 4.3.1 – Period A Productivity Factor Values

Using the data in Table 4.3.1, the group productivity factors are:

$$f\,(\mathrm{L}) = \frac{1(6{,}120/6{,}120) + 1(16{,}320/16{,}320) + 1(14{,}280/14{,}280) + 1(4{,}080\,/\,4{,}080) + 1(6{,}120\,/\,6{,}120)}{(1+1+1+1+1)5} = 0.2$$

$$f\,(\mathrm{Q}) = \frac{1(29{,}300/23{,}437.5) + 1(5{,}625/4{,}500)}{(1+1)2} = 0.625$$

$$f\,(\mathrm{C_w}) = \frac{1(350/350) + 1(1{,}600/1{,}600) + 1(1{,}800/1{,}800) + 1(1{,}250\,/\,1{,}250)}{(1+1+1+1\,)4} = 0.25$$

$$f\,(\mathrm{C_f}) = \frac{1(1{,}750/1{,}750) + 1(750/750)}{(1+1\,)2} = 0.5$$

$$f\,(\mathrm{R}) = \frac{0.934(7{,}500/5{,}250) + 1(100{,}000/75{,}000) + 0.762(350/200) + 1.111(15{,}000\,/\,12{,}500)}{(0.934+1+0.762+1.111\,)4} = 0.350$$

$$f\,(\mathrm{V}) = \frac{0.8(5/3) + 1.185(90/80) + 0.8(5/3) + 1(45{,}000\,/\,33{,}750) + 0.889(6\,/\,4)}{(0.8+1.185+0.8+1+0.889)5} = 0.285$$

$$f\,(\mathrm{M}) = \frac{1(125/125) + 1(200/200) + 1(235/235)}{(1+1+1\,)3} = 0.333$$

Inserting these values into the total productivity index expression the productivity index for Period A can be calculated as follows:

$$\text{PI} = \frac{0.2 + 0.625 + 0.25 + 0.5 + 0.350 + 0.285 + 0.333}{7} = 0.363$$

When compared to the baseline we can see that the overall productivity index increased from 0.319 to 0.363. Since productivity index values greater than 0.319 indicate a gain in productivity it can be surmised that productivity increased by 13.8% in product development as a result of the lean initiatives. Using the same type of comparison for the productivity factor groups we can see that there was no improvement in productivity for Labor, Working Capital, Fixed Capital, and Miscellaneous. The Quality group factor showed an increase of 25% from 0.500 to 0.625, while the Revenue and Value Added groups showed increases of 40% and 42.5% respectively.

If we analyze the results of the individual factors within the groups we can clearly identify correlations between the lean initiatives that were implemented and the benefits achieved. While some initiatives may be considered “soft” and more oriented to organizational and methodological changes there is an indirect impact on the productivity. Other initiatives, which are firm changes to the process, procedures, and standard practices, have clear and obvious direct impacts on certain factors.

The company chose to change their current product development process from a Stage-Gate process to a Concurrent Engineering approach. By doing this they were able to perform tasks and activities within product development in parallel instead of sequentially, significantly shortening the time to develop a product. Although this change required more teamwork, coordination, and up-front contributions between stakeholders, once the processes and procedures were in place it greatly contributed to the percentage of projects meeting the cycle time goals, number of new products developed, and number of patents from new products.

A major change was also made to the design concept process. Prior to the lean initiatives, a few alternate design concepts were developed, and the design concept that matched the product requirements and specification the closest (best fit) was then chosen as the design base for the rest of the development process. This “best fit” design was then redesigned and refined until the final product was reached. This method had created a lot of process waste caused by revising and redesigning the work, which added to the time taken to develop products. This method also led to defects and quality issues in the final product and manufacturing by having a piecemeal, reworked design rather than a cohesive, robust design. To counter this, the company started developing a large number of design concepts at the project start. Each design was tested and analyzed in parallel and eliminated one by one through the development process as they were found to be inferior to other designs. At the end of the product development cycle the process was left with one unchanged design which then goes into production. To support this Set-Based Engineering the company also improved their prototyping and simulation. Starting at the concept phase simple, low cost prototypes were developed for each design. As designs were eliminated and the development progressed, more complex and detailed prototypes were created. Near the final stages of development full, functional prototypes were available for final testing, analysis, and product selection. Through use of prototypes they were able to efficiently test and analyze design concepts and catch potential quality issues early on. The change to Set-Based Engineering and the effective use of prototypes played a major role in improvements to the material and labor rework, the percent of projects meeting the cycle time goals, and the number of new products and patents during Period A.

Two significant changes were made to the parts and materials side of the product development process. In order to increase reliability and quality, and reduce development time, components for new products were first researched to see if they could be reused or repurposed from existing or previous products which have already been tested and verified. If the component didn’t already exist in-house they looked for standard off the shelf components from vendors and suppliers that could be used. As a last resort, if no suitable existing components existed in the market place, only then would the component be designed and manufactured internally to be used on the final product. By using existing components they could eliminate unnecessary design and testing time and could be assured of the quality and reliability of a proven product. The company also instituted a process change in product development where suppliers and vendors became involved in the product development at the early concept/design stages. By doing so, the suppliers' specialized knowledge and expertise helped solve design issues quickly, generated recommendations for cost improvements, and helped identify potential quality issues. These two changes to the part and material aspect of product development contributed to a decrease in rework due to quality issues, and helped to meet the project cycle time goals by saving time and eliminating waste.

An issue the company had prior to incorporating lean initiatives was frequently repeating mistakes, solving problems that had been encountered before and solved, and designing from scratch products/components which had very similar designs to products in the past. To resolve this, the company made several improvements. First, they developed a Knowledge Database where technical, product, and project problems, issues, lessons learned, and their solutions could be logged, stored, and searched for future reference. Secondly, they developed a Design Library where all parts, components, subassembly, and product designs could be stored, quickly searched and easily referenced for future design requirements. As a final measure the company created a handbook for best design practices built upon the history of successful products and the knowledge of their most experienced personnel. The creation of these "Knowledge Transfer" tools prevented quality issues and mistakes, saved valuable time solving problems and designing products, and generated internal cost savings through manufacturing process improvements and product improvements.

Several other improvements were made based on lean initiatives, which were not physical changes to the process or activity. However, these organizational and structural changes to product development have a significant indirect impact on productivity. The company strengthened their project management for product development by using the most experienced and knowledgeable engineers as project managers and holding them accountable for the performance targets as well as budget and schedule. Improvements were made to project and resource scheduling through workload leveling, multi-project management, and capacity planning tools. Project planning was also changed from the traditional top-down approach to responsibility-based planning, where project managers set the major project milestones and individuals resolved schedules for their tasks to meet milestone dates. One of the largest changes was the development of process standards and the optimization of the product development process. Prior to the lean initiatives, each product development project was executed as a unique undertaking. There was no reference or baseline for what tasks were required and how they should be done. This led to inconsistencies between projects, confusion among team members, wasted time, process task variability, and frequent errors due to missed steps or checks. The company developed standard processes, procedures, and associated documentation to ensure all projects followed the same product development path or "road map". While defining the standards they were able to optimize the processes and procedures for each task to remove non-value added steps and reduce waste. The documentation and checklists generated as guides for the processes inherently added quality checks and review points, and ensured the processes and procedures were being followed. Because of the changes in philosophy on how products are developed and the improvement methods that were put into place the company saw benefits in internal cost savings, quality improvements, and reduction in project cycle times. These benefits contributed to overall gains in productivity between multiple individual factors.

4.4 Discussion of the Case Study Results

As noted in Section 4.3 implementing lean initiatives in the case study product development organization resulted in an overall gain in productivity of 13.8% from the Baseline Productivity Index of 0.319 to the Period A Productivity Index of 0.363. Table 4.3.1 shows the impact on the individual factors used to construct the index; these impacts are discussed specifically in this section. Table 4.4.1 identifies which lean initiatives affected each factor used in the model.

Factors / Initiatives	Strong Project Manager	Specialist Career Path	Workload Leveling	Responsibility-Based Planning & Control	Cross-Project Knowledge Transfer	Simultaneous/Concurrent Engineering	Supplier Integration	Product Variety Management	Rapid Prototyping, Simulation & Testing	Process Standardization	Set-Based Engineering
Rework Labor					D		D	D	D	I	D
Rework Material					D		D	D	D	I	D
Stock Value Increases attributable to new products & technological advancements	I	I	I	I		I			I	I	I
% Of Sales Revenue from new/improved products allocated to NPD	I	I	I	I		D			D	I	D
Internal Cost savings for manufacturing process/product improvements (cost avoidance)	I	I	I	I	D					D	
Licensing Fee revenue from new products/technology shared	I	I	I	I		I			I	I	I
# of Patents from new inventions/Products	I	I	I	I		D			D	I	D
"Time to market" for new products - % of projects meeting corporate NPD cycle time goals	I	I	I	I	D	D	D	D	D	I	D
Market share improvements attributable to new/improved products	I	I	I	I		I			I	I	I
Value of Intellectual Property/Knowledge gained through research and NPD	I	I	I	I		I			I	I	I
# of new products developed	I	I	I	I		D			D	I	D

D = direct impact on factor, I = indirect impact on factor

Table 4.4.1 – Effects of Lean Initiatives on Productivity Factors

In the Labor group productivity the results indicate there was no improvement in productivity. The total number of product development employees was 20 in both periods, so the total number of available hours remained the same. Since the company's goal was to increase the outputs (number of products, revenue, patents, etc) and not to decrease the inputs (labor) we would expect the labor to remain constant unless employees are added or removed.

The Quality group productivity factor observed a 25% increase in productivity, from 0.500 to 0.625. Rework from quality issues is commonly expressed as a % of the cost of goods sold (COGS). Based on this, if the revenue increases and quality stays the same, rework costs can be expected to increase. Even though there was an increase in the percent revenue attributable to product development in Period A the rework cost was less than the Baseline. When calculated, we find the company's rework costs decreased from 10% of COGS to 6% of COGS, as a result of cross-project knowledge transfer, supplier integration, product variety management, rapid prototyping, simulation and testing, and set-based engineering. The quality improvements were also indirectly impacted by process standardization.

Both the Working Capital and Fixed Capital productivity groups reported no changes in productivity from the Baseline to Period A. The cost for land, buildings, office did not increase during this time period, and no major capital expenditures were made. To prevent increases in productivity being made by spending money rather than changing what they already had, the company retained the same working capital budget between the Baseline and Period A. Because there were no changes in costs, budgets, or spending between the Baseline and Period A we can expect the productivity factor to remain constant between the two periods.

Overall, the Revenue productivity group showed a total gain in productivity of 40%, from 0.250 to 0.350. Looking more closely at the individual factors within this group we can see that Percent of Sales Revenue from New/Improved Products Allocated to NPD increased from $75M to $100M while the company's annual revenue stayed the same at $500M. This is an increase from 15% to 20%, or a 33.33% gain in revenue from NPD. As we would expect, developing more products within a given time period increase Licensing Fee Revenue from New Products/Technology, as well as Stock Value Increases Attributable to New Products. Stock Value rises due to NPD went from $5.25M to $7.5M, about a 43% increase, while Licensing Fees rose 20% from $12.5M to

$15M. Internal Cost Savings for Process/Product Improvements (cost avoidance) also increased as a result of the aforementioned lean initiatives. Period A revealed an improvement of 75% over the baseline period, although in terms of monetary value it represents less than the other factors with a $150K improvement. Revenue group improvements are attributed to cross-project knowledge transfer, simultaneous/concurrent engineering, rapid prototyping, simulation and testing, process standardization, and set-based engineering. Strong project management, specialist career path, workload leveling, and responsibility based planning and control also contributed to improvements indirectly.

Similar to the Revenue group, the Value Added group showed an overall productivity improvement of 42.5%. The most significant factor within this group is the Percent of Projects Meeting the Corporate NPD Cycle Time Goals. In the Baseline period only 80% of projects met the goal of 8 months from concept to market, after the lean initiatives were implemented this increased to 90% of projects meeting the 8 month cycle time goal. Because more projects could be completed in less time the company was able to develop more products during Period A, which also led to an increase in the number of patents during this period as well. These two factors showed an increase of 50% and 66.7% respectively. As previously mentioned the Value of Intellectual Property/Knowledge Gained through R&D is commonly calculated as 45% of the annual sales revenue attributed to product development. Due to the increases in revenue from NPD this factor increased from $33.75M to $45M, or 33.3%. With the improvements in product quality, reduction in development cycle time, and increase in number of products developed in Period A the company benefited from an increase in market share over its competitors. The overall market share improvements as a result of product development improvements increased from 3% to 5%. As with the Revenue group, strong project management, specialist career path, workload leveling, and responsibility based planning and control, with the addition of process standardization contributed to improvements indirectly. Lean initiatives that directly impacted the Value Added group include; cross-project knowledge transfer, simultaneous/concurrent engineering, supplier integration, product variety management, rapid prototyping, simulation and testing, process standardization, and set-based engineering.

As with the Fixed and Working Capital groups, the Miscellaneous group factor did not show any gains in productivity. The expenses within this group did not increase or decrease with any lean initiatives, so no gains or losses in productivity would be expected within this group.

Did the company meet the goals it set forth in the first step of their lean initiative process? The first goal was to meet the product development cycle time of 8 months for at least 95% of projects. From the analysis we determined that the company improved their product development cycle time from 80% to 90%, but has yet to achieve the 95% goal. The second goal was to increase the number of new products developed per year by 25%. This goal was met as the company witnessed a 50% increase in the number of new products developed in Period A. The next goal was to improve the quality of new products by decreasing rework costs. While the company did not establish set figures for the reduction they did meet the goal by reducing rework costs by 10% of COGS to 6% of COGS. Meeting the fourth goal, to increase the number of products with high market share and payback potential, can be determined by looking at the Percent of Sales Revenue from New/Improved Products Allocated to NPD and Market Share Improvements Attributable to New/Improved Products. These two factors each showed a significant increase, thus meeting the company's objective. The final goal of developing system standards and processes cannot be directly measured by individual or group factors. The company did create product development standards and processes as set forth in their goals and the impact can be indirectly measured by the 13.8% improvement in the total productivity index. While the company met four out of five of its goals, the lean initiatives can be considered a great success. Through continuous improvement the cycle time goal can be met and higher standards can be set for future periods to further increase productivity.

5.0 Conclusions

The goal of this project was to effectively model productivity within a new product development environment and to illustrate how it can be used to measure the impacts of lean initiatives.

A productivity model, based on the work by Koss-Lewis was developed for a product development environment. The model included seven group productivity factors, and twenty-five individual factors. To explore the effects of lean initiatives on a product development organization we developed a detailed, hypothetical case study. The productivity model was applied to the case study data to calculate the overall productivity index as well as the productivity of individual group factors. Through a literature review we then identified eleven lean initiatives that can be applied to new product development. The eleven lean principles were examined to explore how they might generate positive or negative impacts on new product development through process improvements, scheduling and planning changes, material/parts/supplier management, and changes to the methods and practices used in product development. We used the model to demonstrate that applying lean principles to new product development in the case study increased productivity by reducing cost, improving quality, and decreasing the cycle time of developed products.

Research performed through this project revealed the difficulties in measuring productivity within a product development environment, as evidenced by Griliches[42]. By identifying key factors, with available data, a simple productivity model can be constructed to effectively measure productivity within a product development organization, as revealed in this project. To date, measuring the impacts of lean initiatives comprehensively and relative to productivity has been very limited. Most

[42] Griliches: "R&D and Productivity: The Econometric Evidence", University of Chicago Press, 1998

companies use traditional methods of balanced scorecard, KPIs, dynamic multi-dimensional performance (DMP), or traditional management/accounting metrics.[43] Using productivity models, such as the one created in this project, provides a comprehensive view of the overall impact of lean initiatives, as demonstrated in the case study. By applying the model we developed to the data for the case study, we concluded that the benefits of lean initiatives can be measured and analyzed using the productivity model developed for product development. Based on the results from the case study, implementation of additional lean principles and continuous improvement to existing processes to further reduce waste and streamline activities might result in additional gains in productivity.

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