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Lean Thinking For Lead-Time Reduction And Efficient Knowledge Creation In Product Development

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LEAN THINKING FOR LEAD-TIME REDUCTION AND EFFICIENT KNOWLEDGE CREATION IN PRODUCT DEVELOPMENT DOMAIN

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DEDICATION

To My Loving Wife, Annu and

My Parents, and Sister, Radhika for their unconditional love and guidance

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CHAPTER 1. INTRODUCTION

1.1 RESEARCH MOTIVATION

Lean concepts have gained a lot of attention in the past two decades in terms of identifying and removing wastes from manufacturing and many service industries. McManus (2005) stated that a tested theory that puts lean into the heart of a holistic system and has the ability to extend across other elements of an enterprise, such as product development (PD) or knowledge creation, is still rarely mentioned. This is owing to the inherent differences in the working philosophies among them. Direct implementation of lean concepts from manufacturing to other domains is questionable and full of doubts. Lean concepts need modifications to work well in a PD environment. Due to this, studies focusing on tools based on lean thinking concepts which are particularly designed to implement in PD from a pragmatic view are currently lacking. Practitioners are still experimenting by following the philosophy "learning by doing" to see what works and what does not as implementation guidelines have not been laid down yet. The first question this dissertation aims to investigate is:

1) "How lean tools/ methods can help in improving the PD process?"

Continuous innovation intended to deliver products with new attributes is an imperative driver for organizations to remain competitive in today's fast changing, unpredictable and demanding marketplace. It requires an organization to regularly update and create knowledge for the current generation, and reuse it later for the next generation of a product. Both academia and practitioners consider knowledge creation as a key source of growth and an imperative tool to maintain the sustainable competitive advantage. Traditional systems however, have a trivial impact on innovation owing to the absence of any process and/or tool for knowledge creation. This is due to the fact that one can't solve new and unfamiliar problems and issues (arising from changes in the PD phases) with the existing old knowledge. An employee is required to possess knowledge creation ability in order to deal with them. Therefore, exploring methods intended to assist employees in performing tasks excellently by creating and enabling knowledge is a modern challenge faced by many organizations. An important question that needs to be asked here is

2) *"Is there any theory which can be applied to knowledge creation and how lean tools and methods can support efficient knowledge creation"*

Further, a successful innovation is often associated with adoption and execution of all SECI (socialization-externalization-combination-internalization) modes of knowledge creation within any product development phase. All SECI modes are conceptually linked and utilized within distinct product development phases with a view to improve the performance of the end product or service. This dissertation challenges this conventional assumption that all SECI modes affect a PD phase and distinguish different PD phases' affinity corresponding to distinct SECI modes. The research will focus on the third question that still needs to be investigated:

3) *"If there is an effect, can all the four SECI modes be assumed to have a positive influence on improving the performance?"*

This is due to the fact that selection of appropriate SECI mode(s) can significantly affect the efficiency of the strategic planning and help in saving the business resources.

Extensive literature review conducted in these research domains clearly indicates that a very limited work has been done on these topics and therefore research gaps exist. This dissertation is an attempt to bridge these gaps.

1.2 RESEARCH METHODS

The main focus of this dissertation is to customize lean thinking concepts in order to manage, improve and develop the product faster while improving or at least maintaining the level of performance and quality. Lean thinking concepts encompass a board range of tools and methods intended to produce bottom line results however, value stream mapping (VSM) method is used to explore the wastes, inefficiencies, non-valued added steps in a single, definable process out of complete product development process (PDP). This single step is highly complex and occurs once while the PDP lasts for 3-5 years. A case study of gas turbine product has been discussed to illustrate and justify the use of proposed framework. In order to achieve this, the following have been performed: First of all a current state map is developed using the Gemba walk. Furthermore, Subject Matter Experts (SMEs) brainstormed to explore the wastes and their root causes found during the Gemba walk and current state mapping. A future state map is also developed with removing all the wastes/inefficiencies. Besides numerous intangible benefits, it is expected that the VSM framework will help the development teams to reduce the PD lead-time by 50%.

In regard to the second question, an integrated dynamic knowledge model is targeted to structurally define a practical knowledge creation process in the product development domain. This model primarily consists of three distinct elements; SECI (socialization-externalization-combination-internalization) modes, 'ba,' and knowledge assets. The model involves tacit knowledge and explicit knowledge interplay in 'ba' to generate new knowledge during the four SECI modes and update the knowledge assets. It is believed that lean tools and methods can also promote learning and knowledge creation. Therefore, a set of ten lean tools and methods is proposed in order to support and improve the efficiency of the knowledge creation process. The approach first establishes a framework to create knowledge in the product development environment, and then systematically demonstrates how these ten lean tools and methods conceptually fit into and play a significant role in that process. Following this, each of them is analysed and appropriately positioned in a SECI mode depending on best fit. The managerial implication is that correct and quick knowledge creation can result in faster development and improved quality of products.

In regard to the third question, the dissertation proposes an extended Fuzzy Analytic Hierarchy Process (EFAHP) approach to determine the ranking in which any PD phase is influenced from SECI modes. In the EFAHP approach, the complex problem of knowledge creation is first itemized into a simple hierarchical structure for pairwise comparisons. Next, a triangular fuzzy number concept is applied to capture the inherent vagueness in linguistic terms of a decision-maker. This dissertation recommends mapping the triangular fuzzy numbers (TFNs) with normal distributions about X-axis when the pessimistic value of one TFN is less than the optimistic value of other TFN ($t_{23} \leq t_{11}$). This allows us to develop a mathematical formulation to estimate the degree of possibility of two criteria as opposed to zero resulted by the use of the current technique in the literature. In order to demonstrate the applicability and usefulness of the proposed EFAHP in ranking the SECI modes, an empirical study of development phase is considered. Five criteria and their 19 sub-criteria for measuring the phase's performance are identified based on both an extensive discussion with subject matter experts (SMEs) and a rigorous literature search. After stringent analysis, we found that the combination mode was the mode that highly influenced the development phase. Based on the analysis results, this dissertation also discusses the application of lean visual tools that can be used to improve the knowledge creation during development phase.

1.3 ORGANIZATION OF DISSERTATION

Chapter 2 first reviews the problem statement and the relevant literature related to product development, lean concepts application in manufacturing and engineering. A brief summary of product and ABC company background is provided next. Implementation procedure of lean thinking concepts (VSM) as a strategic decision making tool for the underlying problem are discussed in next section. The analysis of current state reveals numerous inherent wastes that helped in developing future state. The expected results of future state are compared with that of current state to quantitatively measure the improvements. Finally, highlights of the expected benefits after implementation of proposed model from the managerial perspective are also offered.

Chapter 3 section one presents the relevant literature related to knowledge management and lean in the product development in order to identify the research gaps. Then, an integrated dynamic knowledge SECI model is provided to capture the knowledge creation process in practical settings. This model builds the foundation for analysis. Next section offers a summary of lean product development. Further, highlights the research methodology of implementing lean tools and methods in the underlying model are summarized. Details of implementation analysis with the expected benefits from a managerial perspective are also detailed.

Chapter 4 section one presents an argument against the established notion of executing all SECI modes in each product development phase. The next section reviews the relevant literature of knowledge creation, AHP and fuzzy logic. Highlights of the SECI model for knowledge creation are also discussed. The rationales behind selecting the each criterion (sub-criterion) in the problem formulation are also listed. Intensive review of available research and a prolonged discussion with SMEs from strategic decision areas are conducted before picking the criterions and sub-criterions. The implementation of proposed EFAHP method as a strategic decision making tool is detailed. The quantitative analysis results and discussion with expected benefits from the managerial perspectives as well as lean tools are provided.

Chapter 5 summarizes the outcomes of this research, and suggests the scope for the future research. The contribution and limitation of this study has been discussed.

CHAPTER 2. VALUE STREAM MAPPING TO REDUCE LEAD-TIME

2.1 INTRODUCTION

Owing to the fact that products launched earlier capture the major market share achieving thus a phenomenal success (Kotler, 2003). Organizations are witnessing a scenario of maintaining or enhancing the product quality and reducing the ‘‘time-to-market’’ (TtM) parameters simultaneously. In order to achieve the aforesaid goals (enhancing quality and reducing TtM) for long-term success and sustainable competitive advantage, product development (PD) has continuously been emerged as an area of research for both industry and academia (Droge et al., 2000; Tyagi et al., 2013). PD has always been a challenging task and, surprisingly every organization considers it as a primary tool to surpass the competition. In general, PD aims to bring a new/enhanced product or a variant of a product(s) to the consumer.

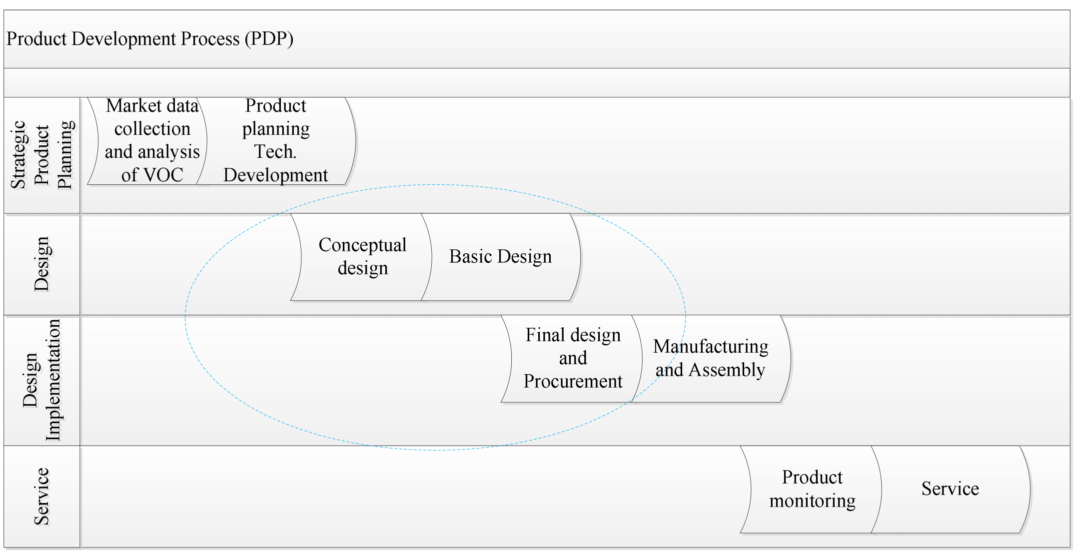

Figure 1: Stages involved in a product development process

In PD, emphasis is set on the design and development of a product aiming to achieve several key criteria such as mapping of customer requirements, quality, technology development, product strategy, cost, interface management, etc. (Clark and Fujimoto, 1991). PD comprises of a sequence of steps/activities where new/incremental product ideas are conceived, investigated, taken through the design process, manufactured, marketed and supported through aftermarket services (see Figure 1). This whole process which starts from market research to delivery is termed as the product development process (PDP). Each organization adapts the structure of PDP to suit their specific needs and capabilities from one product to another. PDP typically follows a framework defined in a sequence of review phases (such as design and gates) to assure the implementation of a structured project management process.

In order to be sustainable and competitive, an organization has to effectively improve the TtM parameter. In this context, lean thinking concepts have gained a lot of attention in the past decade in terms of identifying and removing wastes from manufacturing and many service industries (Kennedy, 2003; Morgan and Liker, 2006). Particularly, the implementation of lean thinking concepts in manufacturing has turned out to be a more enduring advancement of earlier research works (Khalil and Stockton 2010). McManus (2005) stated that a tested theory that puts lean thinking into the heart of a holistic system and has the ability to extend across other elements of an enterprise, such as product development, is still rarely mentioned in the literature. This is owing to the inherent differences between manufacturing and product development, and so it is worthwhile to compare the two to notice the distinctions (see Table 1). For example, in the former, loopbacks are associated with wastes and considered to be a diminishing contribution, however in the latter, loopbacks could be associated with gaining important dynamic knowledge. Hence, direct implementation of lean principles from manufacturing to product development is questionable and full of doubts (Radeka, 2012). Therefore, lean thinking concepts need apposite modifications to work well in a PD environment. Studies focusing on tools based on lean thinking concepts which are particularly designed to implement in PD from a pragmatic view are currently lacking and so an immediate attention is required. Practitioners are still experimenting by following the philosophy "learning by doing" to see what works and what does not as implementation guidelines have not been laid down yet. Moreover, the related works only offer trivial discussion and guidance to implement lean thinking concepts such as value stream mapping in PD but exhaustive results and analysis are not found. Extensive literature review conducted in this research domain (see section 2) clearly indicated that very limited work has been done in the area of lean applications in PDP and therefore a research gap exists.

Table 1: Inherent differences between manufacturing and engineering

Lean Principle	**Manufacturing/production**	**Engineering**
Value	Visible at each step, defined goal	Harder to see, emergent goals
Value stream	Parts and material	Information and knowledge
Flow	Iterations are waste	Planned iterations must be efficient
Pull	Driven by takt time	Driven by needs of enterprise
Perfection	Process repeatable without errors	Enables enterprise improvement

Keeping the aforesaid facts in mind, this research attempts to bridge this shortcoming and research gap by presenting a qualitative framework and illustrating its application. The proposed framework focuses on the practical implementation of lean thinking concepts while aiming to identify and eliminate the non-valued added steps (wastes) in a PDP to minimize the lead-time. The wastes are mainly explored by drawing a value stream map of as-is state using the Gemba walk. The "as-is" map assists in capturing the snapshots of how things are currently done and areas of potential improvements. Future state map is also developed by incorporating all the proposed improvement ideas. One of the ultimate aims of this research is to help the chosen company ABC in their long term goal to meet the PD lead-time requirements of product X at generation Y to achieve a competitive advantage among its competitors.

The scope of this dissertation lies within a single and definable process extracted from a complete PDP. Based on past experience of SMEs, on a selected process segment Pareto chart analysis and brainstorming were conducted. In addition, a detailed discussion was done among SMEs before selecting the process unit which needs immediate attention and that has high potential for improvement. The selected part of PDP plays an important role in deciding the PD lead-time, and thus ensures timely delivery of the product to the customers. It also involves the higher number of human resources as it requires participation of multiple departments from the business network. Moreover, a larger number of iterations are required at additional cost and time to attain a certain level of quality and maturity in the execution. Rework without proper sequencing during steps execution affects the final product quality. It requires the downstream partners to wait causing further delays, affecting the PD lead-time. Therefore, the performance of other departments highly depends on this portion of PDP. Based on the aforesaid reasons, the authors also believe that here lies the highest potential for improvement. A manufacturing-based PD processes for Gas Turbine (GT) products are primarily considered in this research. Such processes generally consist of the activities that: (a) determine whether a new product is required to serve some needs (b) conceive a concept for that product based on customer's requirements identified after a complete market analysis (c) develop all the technical specifications (d) validate both design and production (Yang, 2007). These products have general characteristics such as a complex module structure, a long development cycle time, a long lead time in production, and high costs in parts; whereas these processes are characterized as highly complex to organize and manage.

2.2 LITERATURE REVIEW

Product development (PD) is not a modern area of concern rather it has been an area of active research for decades (Imai et al., 1985; Wheelwright and Clark, 1992; Fleischer and Liker, 1997; Langerak and Hultink, 2005; Tyagi et al., 2013). PD performance is basically accessed in terms of three key criteria, namely: quality, cost, and lead time. In simple terms, the prerequisites to sustain successfully in tough competitive marketplace in 21st century are higher product quality, lower cost and on-time customer delivery (Roemer et al., 2000). PD is among the most utilized research domain to improve PDP with a view to achieve the aforesaid goals (Barczak and Kahn, 2012; Cankurtaran et al., 2013; Agarda and Bassetto, 2013). An efficient PDP is simply an enabler of better products with improved quality at cheaper cost. However, a number of obstacles prevent PDP from being under control and well managed. These obstacles have plagued many companies for years.

To tackle these obstacles, the authors investigated many models of PDP in the literature (Clark and Fujimoto, 1991; Wheelwright and Clark, 1992; Anderson and Pine, 1997; Ulrich and Eppinger, 2000). Clark and Fujimoto's (1991) PDP contains four major development phases: concept generation, product planning, product engineering, and process engineering. Wheelright and Clark (1992) merged the last two phases (product and process engineering) of Clark, and Fujimoto's (1991) model into one phase and introduced a new fourth phase named pilot production/ramp-up. Anderson and Pine (1997) proposed a recommendation of minimum five phases in a development model whereas, Ulrich and Eppinger's (2000) generic model contains exactly five phases: concept generation, system level design, detail design, testing and refinement, and production ramp-up. All the aforementioned models cover the PDP at most upto production/ ramp-up but they do not consider the service phase. Service is one of the critical phases for certain products, such as Gas Turbine (GT), airplane, and car since it could last over two decades. Approximately 80% of business profit comes from this phase (Cai et al., 2011). In GT service stage typically a designer continuously works on upgrading design of parts or modules of a gas turbine, based on the feedback of performance about current product(s). An advanced PDP model extended to include service phase proposed by Cusumano et al., (2012) is adopted in this research (see Figure 1). This research considered the vital phases of PDP such as conceptual design, detailed design, review and validation among all process steps. Surely, Lean Thinking (LT) concepts extended on PDP not only help the front end users who collect the consumer needs, brainstorm, and develop concepts but also provide input to the back end where transition from design to production occurs. However, in this study the special needs of these phases are not targeted. Clearly, they can get benefits from lean analysis in future endeavors.

As mentioned earlier, an organization has to effectively improve the time-to-market (TtM) parameter to remain competitive. The greatest reduction in TtM occurs when an organization streamlines its processing stages, undertakes activities in parallel, and proactively launches the product in the market (Towner, 1994). In regards to streamlining processes, Toyota Production System (TPS) has gained a lot of attention from manufacturing and from many service organizations (Smith and Reinertsen, 1998; Kennedy, 2003; Morgan and Liker, 2006). TPS mainly assists in identifying and removing wastes embedded into process, product design, and policies without offering any value (Kennedy, 2003). TPS or lean thinking thus emerged as an effective and efficient way to continuously decrease costs and improve profits by utilizing the minimum required level of essential attributes like time, space, machine, equipment, and energy to produce a product or to provide a service. The value of a product also increases when wastes pertaining to transportation, inventory, waiting, overproduction, over-processing, defects, and rework are eliminated (Sullivan et al., 2002). It is evident in literature that effective application of lean thinking concepts is a powerful enabler of performance improvement though their application is not a strategy themselves.

The lean thinking (LT) term was first coined by Womack et al., (1990) in his book "*The Machine That Changed the World.*" It refers to the fundamental concept of the waste minimization by questioning the basic understanding of business and manufacturing. Womack and Jones (2003) proposed the five lean principles which are: (1) specify value, (2) identify the value stream and eliminate waste, (3) make the value flow, (4) let the customer pull (value), and (5) pursue perfection. They have emphasized that the term "lean" mainly depends on one critical starting point called "value." Value can be defined only by the customer, and it can measure the manufacturer's efficiency when the product is delivered at a reasonable price at an appropriate time in the right amounts. The term lean thinking is also compatible with many other manufacturing techniques, such as Agile Manufacturing, Just-in-Time Manufacturing, Synchronous Manufacturing, World-Class Manufacturing, and Continuous Flow (Kumar et al., 2006). Russell and Taylor (1999) mentioned many lean tools like one piece flow, VSM, poke yoke, standard work Kaizen, and visual control to minimize the waste in manufacturing. In addition to manufacturing (Panizzolo, 1998; Seth and Gupta, 2005; Herron and Braiden, 2006; Worley and Doolen, 2006; Demeter and Matyusz, 2011), many other sectors such as software development (Poppendieck and Poppendieck, 2007), project management (Ballard and Howell, 2003), healthcare (Bamford and Lodge, 2007), supply chain management (Cudney and Elrod, 2010), energy management (Quinn, 2012), environmental management (Yang et al., 2011), semi-process industry(Pool et al., 2011), food industry (Simons and Taylor, 2007), shipbuilding (Storch and Lim, 1999), aerospace (Houlahan, 1994), public services (Radnor and Boaden, 2008) etc. also have been benefited by lean thinking concepts and tools. Abdullah (2003) demonstrated VSM and lean manufacturing application in process industry specifically in steel industry. Among many lean thinking tools and methods, VSM has been very successful in pinpointing the wastes and improving the processes due to revealing nature of used metrics and flow. The main goal of developing VSM tool was to explore the interdependencies of two separate departments and tackle the situation where conventional industrial engineering tools to capture the holistic view were negatively found (Seth and Gupta, 2005; Singh et al., 2011).

According to the literature, on an average, it takes around 4-5 years to develop a new product (gas turbine) while about 50% of costs incurred tend to be spent on wastes (Anand and Kodali, 2008). A plethora of research in the literature proposed methods to reduce PDP lead time and wastes (Millson et al., 1992; Maylor, 1997; Droge et al., 2000; Langerak and Hultink, 2005; Tyagi et al., 2011; Cai et al., 2011; Tyagi et al., 2013). Some successful and efficient methods, tools and techniques were brought up concerning different issues pertaining to PDP (Syan and Menon, 1994; Voss et al., 1995; Zhang and Yu, 1997; Zussman and Zhou, 1999; Tyagi et al., 2012). However, no general solution exists in an organization to solve complex problems. An ambiguity on how to select best suited tool(s) for improving PDP still prevails. As discussed above, Lean thinking has been successfully implemented in manufacturing environment (Seth and Gupta, 2005; Worley and Doolen, 2006; Kumar et al., 2006) and also has a huge potential to reduce TtM factor in PD. However, there are many distinct differences between PDP and manufacturing process, so lean principles have to be modified to work well. The already proven best tools such as VSM have to be further scrutinized, studied, customized, and integrated into PDP. Undoubtedly, there are many lean tools which are being developed and implemented or are in the implementation phase. Nonetheless, after a detailed discussion with the working group on PDP, the output was a consensus on adopting VSM to help guarantee success in improving PDP.

Techniques such as concurrent engineering (Tyagi et al., 2013), total quality management (Voss et al., 1995) etc. have been implemented and quite successfully improved the performance of PDP. However, there is still a shortfall in the expected or desired advancement to take PD to the next level (Worley and Doolen, 2006). Such shortfall is believed to be bridged through the implementation of lean thinking concepts namely VSM. It is evident from the literature review that except McManus (2005) not much emphasis has been laid on LT concept implementation in the PD environment. Thus, the main objective of this research is to report preliminary approaches and expected results of our contribution towards a systematic and formal lean implementation. In this regard, the major focus is on VSM among lean tools as it is one of the most important concepts implemented successfully in various sectors. VSM framework contains a large number of principles and methods in its structure. The authors outline a comprehensive strategy that combines many lean tools, and several sound principles (see Figure 2) (Haque and James-moore, 2004; Huthwaite, 2004). VSM is mainly used to identify the potential areas for improvement by exploring and removing the wastes in a PDP, while other tools are used to conduct analysis. The goal here is to implement lean tools beyond just the identification and reduction of waste, but to support value creation of sustainable products and foster quality. In the next section a generic framework of VSM implementation that addresses most of the concerned issues is proposed.

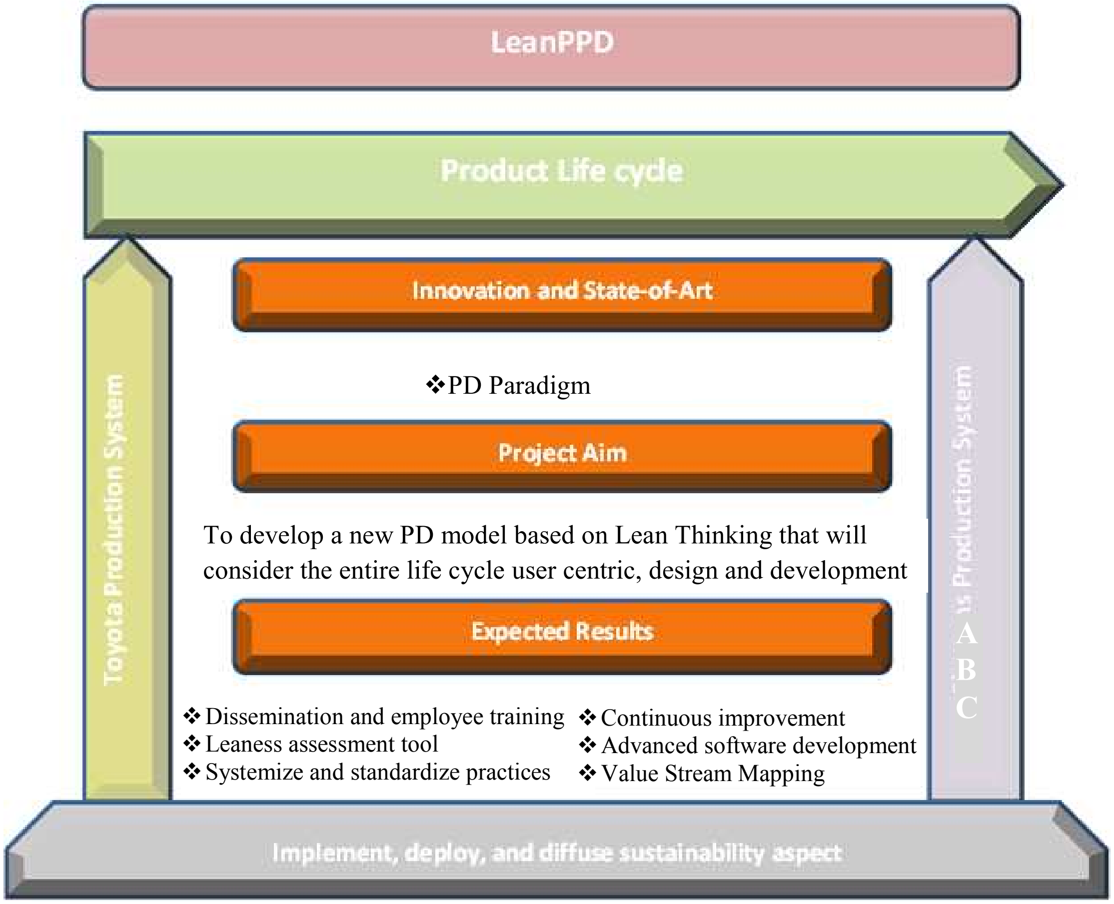

Figure 2: Summary of PD model (Shehab et al., 2010)

2.3 ABC COMPANY BACKGROUND AND BUSINESS

The unit under this research study is a part of a large organization (ABC) which is stretched into diversified areas including healthcare, energy, consumer products, construction, and financial products, etc. This unit is a branch of the energy sector established in early period of 20th century and currently has more than 200,000 employees in more than 100 countries. This company develops and produces a wide range of gas turbines (GT) classified on the basis of maximum output (A MW to B MW) to fulfill the diversified demands of customers based on their needs. It is a leader in developing, producing and supplying GT products and presently covers a market share of more than 40%. In the earlier phase of last decade, GT accounted only for 15% of the power generation industry. The current demand of GT products has witnessed a significant increase soaring upto 40% by the next two decades according to a data published by Department of Energy (DOE). It is required to increase the annual GT production by more than 2.5-3% to match the demand worldwide. This scenario is putting a huge amount of pressure for efficient PD to avoid any threat from the competitors regarding cheaper and faster products. The PD time for GT variant X is 4-5 years. The company further wants to reduce it to beat the competitors and to gain a larger market share. In order to achieve these objectives, companies have already started to critically explore, develop, customize, and modify various tools and methods that fall under the category of TPS. Keeping this in mind, company ABC wants to use VSM to explore the wastes in PDP and eliminate them. The next section will present the current state map and future state map for a manageable portion of PDP.

2.4 VALUE STREAM MAPPING TO DEVELOP "AS-IS" STATE

The advent of value stream mapping (VSM) has replaced conventional recording approaches from an analysis perspective. This is due to the fact that VSM provides a visual platform to capture the input/output of "door to door" steps, involved resource, cycle time and utilized time. As stated earlier, the five lean management principles forming the backbone of VSM are: preciously defining value for your product from customer's point of view, developing value stream and eliminate wastes; uninterrupted flow, avoiding push to customers rather letting them pull and pursue to reach the perfection level (Womack and Jones, 2003). Based on lean thinking principles, the tasks performed in PDP can be classified into the following 3 categories: 1) Value added: This category of tasks are the ones that really move product design forward and create values that external customers are willing to pay in order to get their job done; 2) Non value added but necessary: This category of tasks are the ones that may not move the product design forward and may not create values that external customers are willing to pay, but they are necessary under current circumstances; 3) Waste: This category of tasks are the ones that does not move the product design forward and they have no value for external customers. These tasks should be identified and eliminated.

Mascitelli (2007) stressed the importance of increasing the ratio of value-added time, and to decreasing the ratio of non-value added but necessary and the waste. Mascitelli stated that based on industry survey, in an 8 hour working day, the average value added hour is only 1.7 hours in the Western companies. However, Toyota claimed that its average value added time is more than 50% (Womack and Jones, 2003). In order to reach that state, expectations are to find wastes associated with the information flows in PDP analogous to the seven wastes identified in the factory (last waste is in addition to traditional waste). The wastes related to information flow are considered in this research because during development projects primarily the information is exchanged among cross-functional team members instead of any physical products. The seven info-wastes include (Womack and Jones, 2003):

- Overproduction: Creating too much of information
- Inventory: Having more information than you need
- Extra processing: Processing information more than required to get an indented output
- Transportation: Moving information from one place to another place
- Waiting/queuing: Waiting to process the information or waiting to get the information
- Excess motion: Moving of people to access/process the information
- Defect/rework: Error or mistakes that causes to redo the efforts to correct the problem

- Underutilized people: The employees are either not assigned or have a very limited roles. However, in reality they are more skilled and capable to handle more if the process has been responsibly designed more effectively.

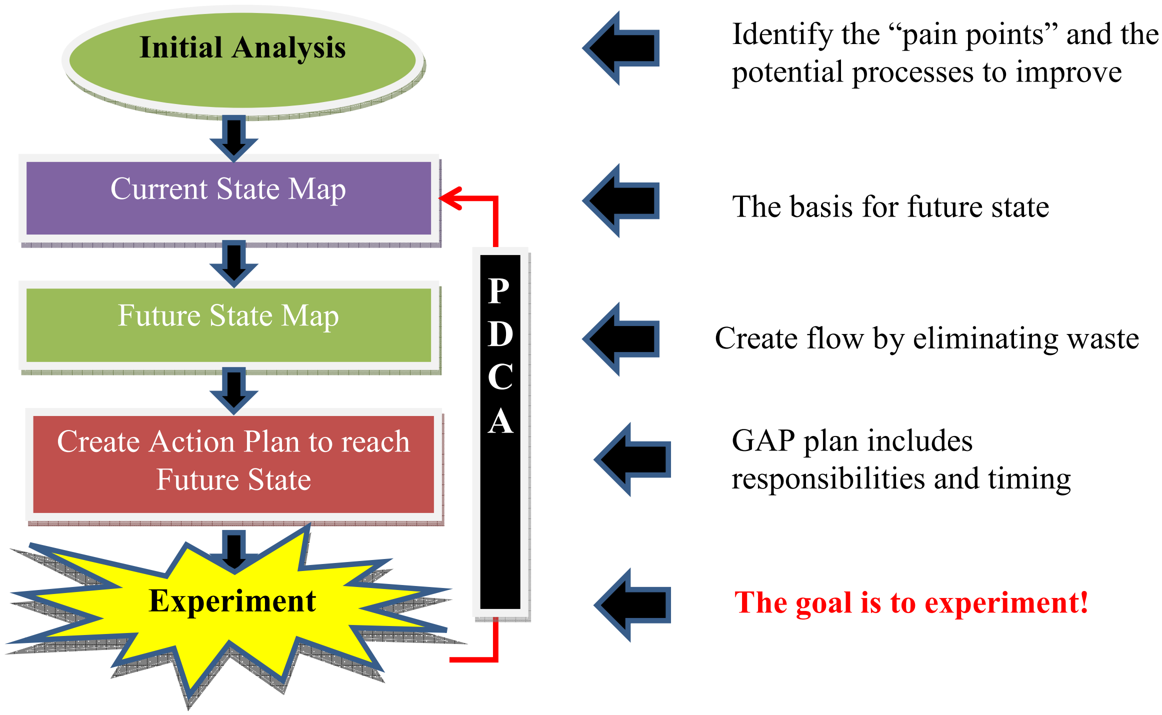

Figure 3: VSM implementation phases and their respective objectives

Figure 3 shows the high level steps involved in implementation of VSM and their objectives in a single but definable process out of a complete PDP are detailed in Table 2. The initial analysis (scan and plan) was conducted to identify the main pain points and select a bunch of potential processes for improvement. The Pareto analysis was conducted to prioritize the processes based on the total time in the systems and total cost of resulting component. In the next step, the current state is mapped with the prospect of reaching to the future state. The objective is to create an action plan to reach the future state and realize all the benefits by eliminating wastes. Some experimentation using PDCA (Plan Do Check Act) cycle are also performed to gain better results in reaching the future state. Next sub-section discusses the Gemba walk for the underlying study.

Table 2: The planning for VSM: tasks, output and their objectives

Description	Tasks	Output	Objective(s)
Initial analysis	Review of business plan, strategy, key metrics etc	High level picture of workspace	Get familiarized with process and business
Process walks	A physical walk through the PD workplace noting the current high-level organization design for flow of people, information, services	A picture of organization identifying high level flows and the waste associated with the current PD design, including the review of appropriate documents	To collect the finite possible processes in detail.
Process Quantity Analysis (PQA)	Breakdown P.D. services into "families" which have the same process steps and similar process times. Determine various process cells required to deliver the best value proposition Define natural sequencing of activities	A matrix of the current mix of PD processes Potential product family solutions based on common routings (sequencing & time) Consider potential flow improvements to processes	The objective is to select vital few from trivial many processes to focus on important. Pareto analysis can be helpful.
Process walks	Review deeper levels of the process in the Gemba to confirm initial improvement ideas	Achieve better understanding of the potential improvements for the VSM	Break down the vital few into small steps to find the root cause of problem and find wastes. Important tools are: Brain storming, Fishbone diagram, Fault tree analysis, 5 Why's, Failure Modes and Effects Analysis, Pareto chart
Action plan	Determine action plan for VSM workshop	Finalize action plan including next steps, resources and timing for VSM workshop	Make a plan to solve root causes of problems & remove waste to reduce lead-time & improve quality at cheaper cost.

2.4.1 Pareto Diagram

Pareto diagrams are very specialized forms of column graphs. They are used to analyze a problem from a new perspective, focus attention on problems in priority order, compare data changes during different time periods, and provide a basis for the construction of a cumulative line. They are predominantly used for prioritization purposes after identifying major problems (or opportunities) and ranking them. They can help teams get a clear picture of where the greatest contribution can be made. For the underlying problem, a list of component was selected and corresponding time in system and total cost was calculated (see Figure 4).

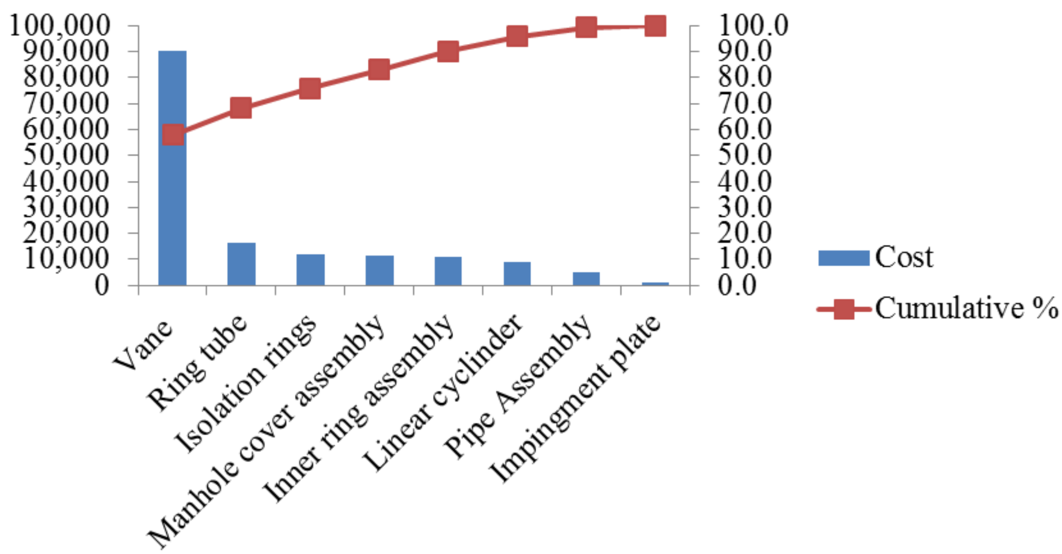

Figure 4: Pareto analysis to select the underlying process

From the Figure 4, it is evident that vane components are constitute around 70% of the total cost and hence are the focus of this research.

2.4.2 Gemba Walk for Scan and Plan

Gemba refers "*the real place*" where the actual action is executed. The effective use of Gemba encourages the "go-see" principle. It means getting out of office and walking the process with concerned people, to help them discover issues and fix them. It became a mechanism for "*catching*" people doing the right things and getting recognized for it. Gemba walk has two fold advantages. First, it is a powerful way to support continuous improvement and process standardization with the help of company leaders, managers and supervisors. Such practice of being in continuous touch with team players helps in keeping an eye on real development issues in business and in resolving them as soon as they surface. It helps building relationships with team leaders by getting to know teammates better and helping them improve the processes. Secondly, alignment of efforts of all team members is ensured. This is fundamental to improve the effectiveness of people and to discover opportunities for improvement by asking questions and listening to the answers. When an interest is shown by senior leaders, the team is encouraged and thus performance is improved. Moreover, it improves morale by actively showing respect for people visibility and concern about how things are being implemented.

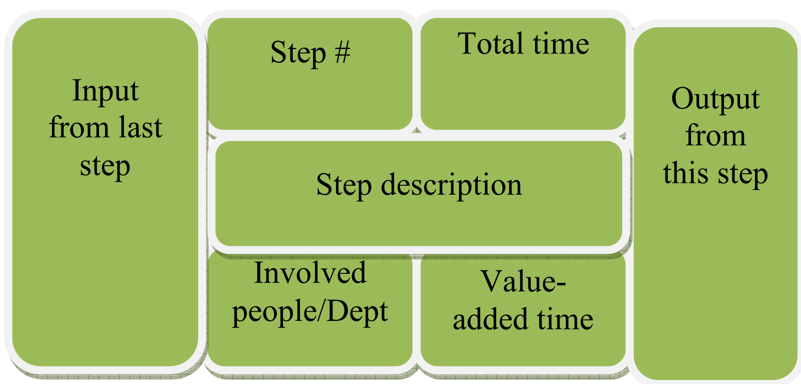

Figure 5: Template to collect the data during Gemba walks

For this particular problem, SMEs from the involved departments as representatives were invited for a three days long workshop. These experts were gathered in a large room and were asked to provide their feedback about the current process without any hesitation. Such freedom was really necessary to get to the bottom of the basic problem. Further, all the issues were noted down and were categorized using Affinity Diagrams. The affinity diagram is widely exploited during the planning stages of a problem to organize information. It links the generated ideas and gathered facts in an organized way to form the thoughts pattern, similar to the mind mapping techniques. After a dialogue within the team and with the management support, these issues were screened to a manageable list. Since all these people were from a different department their knowledge about VSM concepts were at different levels. Therefore, to keep all the participants on the same page, lean and VSM fundamentals were introduced to everyone. In this presentation, the philosophy and basics behind VSM were explained. Keeping these basic facts in mind, the team did the Gemba walk and each team member was assigned with a particular role such as scribe, process guide, waste identifier, etc. Each member was also assigned with a very specific template according to their role. Such templates were developed in advance with the help of people who have an experience in lean/VSM. Three Gemba walks series conducted during this endeavor. These walks gradually moved down to the specific processes which were the target for improvement.

2.4.3 Current State Map

Once the Gemba walk was completed, all the team members again gathered in the same room and discussed about the steps identified and written down on templates. These steps were further noted down on a sticky note and put on a large white sheet of paper on the wall. The advantage of using sticky notes was the freedom to change the order in case there were any updates. In order to complete one step, seven sticky notes of different colors were used as shown in Figure 5. This figure shows the template used to select the data during Gemba walk. Here the first box shows the input information from the previous step which can be in form of action items or documents. The next box is the step number in the Gemba walk. The involved people or department is listed in a box just below it. The next two boxes contain the information about total time taken to execute the step and what amount of time is value added. In between these two boxes, there is a box that has step description. This step has the brief description of conducted action items. Since in the development process it is difficult to capture the exact information about value-added and waste related data, these values are thus approximated. Due to confidentiality reason, the data has been modified according to a certain rule. The data for current state is summarized in the following Table 3.

For the problem at hand, the sticky notes were used in order to collect all the issues in an organized way. Every issue was discussed and written down on the sticky note and posted on the chart paper. For visualization purposes, standard icons are used to follow the information flow instead of physical materials to achieve operational excellence by brining all the problems to the surface. A current state map - basically a high-level description of a business process- is developed with a view to have deep insights into the present situation of product X (see Figure 6). It offers a clear outlook on current process so that opportunities for improvement can be explored by revealing and visualizing problems. The figure 6 evidently reflects the process steps and their various attributes like waiting time, total time taken to execute a step, value added time, involvement of different department and information flow. The figure provides a holistic view of process steps which are not viable, for example; uncertainties or interdependencies in iterative flows that may be beneficial to create value in overall enterprise efforts. It also helps in visualizing the effects of experimentation on the as-is state in attempting to incorporate the improvement ideas. This experimentation provides a roadmap and guidance for the future state by filling up the gap areas and eliminating all obstacles that prevents flow from pragmatic view. Although it seems simple, the real challenge lies in identifying and defining what wastes are, in finding the reasons for filling information gaps and in overcoming those gaps to reach to the future state.

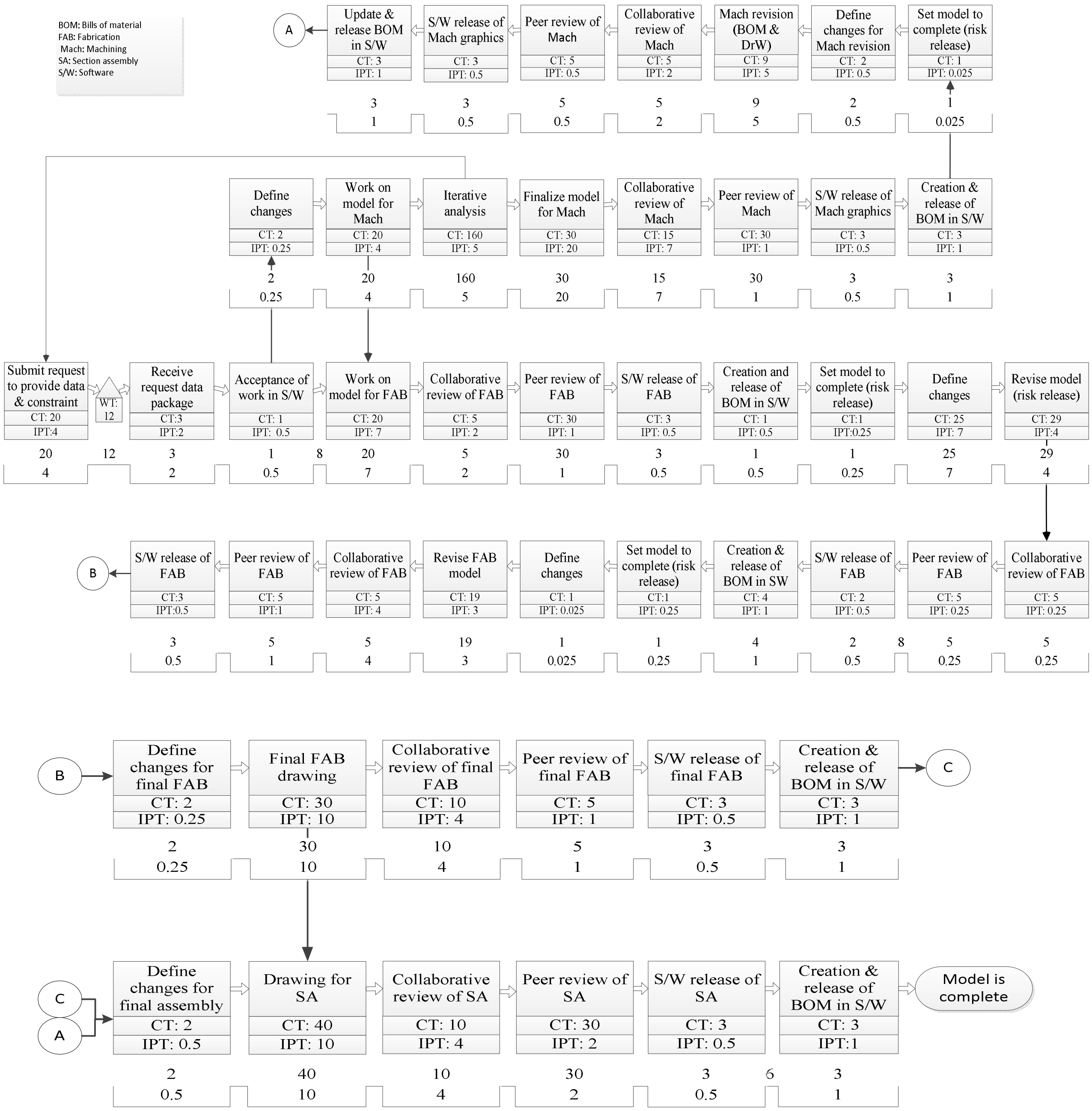

Figure 6: Current State Map for targeted process and associated data (Modified)

2.5 ANALYSIS OF CURRENT STATE TO DEVELOP FUTURE STATE

Qualitative research has been widely used in the business and organizational studies. The qualitative data are usually obtained through face-to-face interviews, observation, and documentation (Barczak and Kahn, 2012). It is considered to be particularly useful in understanding complex environments such as PDP containing "many contextual contingencies, variations, and interactive issues." A PDP is a complex, and expensive process. It takes longer to finish due to many last-minute surprises and delay in the product development cycle targets and engineering deliverables (parts list, structured bills, routings, drawings, visual aids, or material specs). This dissertation attempts to discuss both problems and solutions in a PDP from a pragmatic point of view. All the research conducted in this dissertation is done by a member of a group who has been directly involved in the PDP. However, to maintain the confidentiality, the problems and solution approach have been intertwined with pragmatic and theoretical concepts as well as data sets, and the obtained results have been modified. During the six months research study through observation, analysis, team meetings, and discussion with other stakeholders, many obstacles and problems have been identified in the working philosophy and protocols. However, main obstacles associated with PDP that prevent from achieving desired targets are: (1) failure to assess/identify customer needs accurately in timely manner; (2) lack of good internal communication and control; (3) absence of a formal PDP implementation and new tools; (4) lack of early customer/supplier involvement in the PDP; (5) lack of skilled staff training and development; failure to recognize PDP as a total company activity, rather as a functional project; (6) issues associated with PD are not communicated effectively outside the engineering organization; (7) failure to identify and manage design risk; (8) too many systems usage; (9) lack of standardized processes; (10) requirements of excessive reviews and verification; (11) change in priorities or requirements causing rework towards the end and many more unaccounted elements.

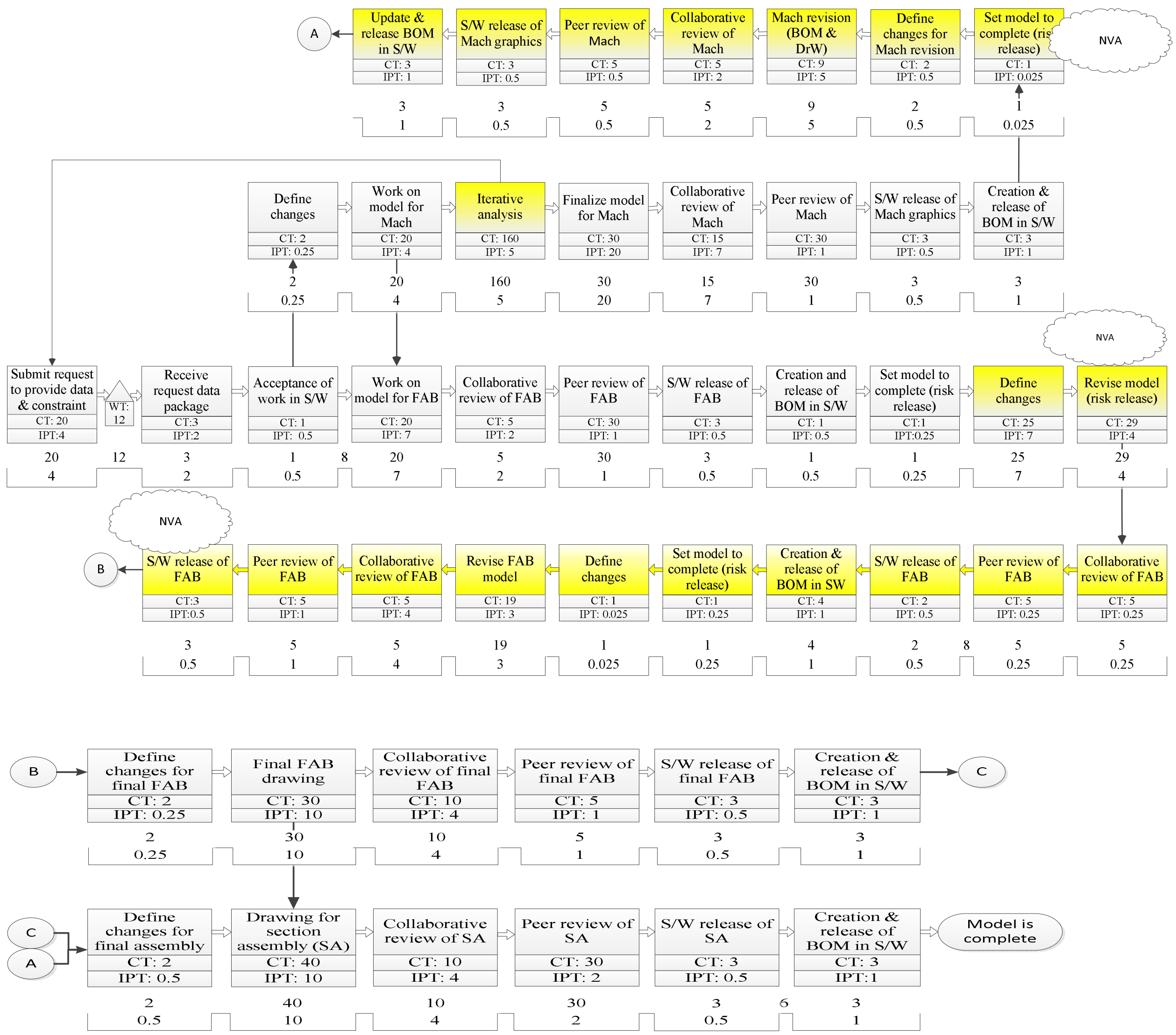

Figure 7: Analysis of current state map (Modified)

A few assumptions are made for the analysis purposes only that are as follows: 1) most of the obtained data is collected from the user's computer. Rest of the data is collected during interview based on the memory of the power user which may not exactly reflect the associated values. 2) Affects due to variation of data are not considered in this study. The data for the product variant X at generation Y could be different for the other variant(s) of the same product family. However, it is assumed that data remains the same for next generation of the product even though it will have few fundamental changes in the design and configuration. The information for various selected criteria to measure the performance of current estate map of for target part of the process is shown in Table 3. This information comes from the current state or “as-is” state shown in Figure 6. Total number of steps involved in current state map is 48, out of which only 10 steps are completely value added (20%). As shown in figure 6, total time in system or lead time is 620 days while cycle time or actual processing time which adds value is only 122.55 days. Most of time is spent on waiting for information, decision or processing over information or duplicate information, rework due to early release of information. Total amount of waiting time is thus 272 days which is mainly caused by 72 required hands-off due to cross-functional team involvement. Moreover, the right people from the cross-functional teams were not involved from the beginning of the project. The project is sent back by a month at every instance when new members from cross-functional team join. This time mainly goes into bringing them upto speed about the current status of this project. Additionally, their input also requires conducting rework, thereby augmenting the lead time. Another major reason for the waiting time is due to the fact that engineer’s roles/responsibilities were not clearly defined in the beginning. This makes no one to take ownership for the work required and causes delay.

Additionally, there are 17 iterations of different steps that constitute for 160 days of the total development time. The reason for the iterations is that deliverables are not clear upfront and engineers were lost in using hit and trial method to reach the final state. This situation is further marred by absence of no knowledge base which can be used as a start point and design can be built on top of that. Decision-making was slow and required multiple design reviews, validation and approvals by personals from the senior manager. It was difficult to get approvals on paper since most of the time those personals were on travel or tied up with other duties. The information is duplicated and released into different software's which is a pure waste and can be eliminated easily in future state. In Figure 7, the yellow box shows the step which is waste but which may be required afterall. From the figure, it is clear that this process involves a large number of non-value added steps. In the future state, numerous non-value added steps are deleted or modified to reduce the PD lead-time. Subsequently, future state is shown in Figure 8 and the corresponding data is shown in the Table 3 with improvements as compared to current state.

2.5.1 Improvement Ideas to Reduce the Product Development Lead Time and Future State

Once the current state map was developed, brainstorming was conducted in the same room, to come up with ideas to reach to the future state.

2.5.1.1 Brainstorming

Brainstorming is a popular and effective tool to generate creative solutions by looking at the problem in novel ways and utilizing the diverse experience of all team members involved. It assists in deep diving to explore the root causes and increases the richness of ideas to obtain better solutions. It is particularly useful to break out stale and established patterns of thinking to overcome many of the issues that can make problem-solving an unsatisfactory process. It creates a positive and rewarding environment for problems solving and making it a fun task with improved bonding among team members. Additionally, active involvement of all the team members in developing the common solutions helps to get categorical buy in from them. Everyone was excited to provide their input.

After initial screening of brainstormed ideas, following points were listed to keep in mind to improve the current state: 1) specify deliverables explicitly at the start to conduct the right analysis at the right time. This will obviate the need of iterative analysis, reducing the frustration level of engineers. Iterations can also be reduced by quick and effective decision-making by senior managers. Of course, it is not possible to eliminate the iterations since the information is updated regularly in development projects but careful attention upfront can significantly reduce additional rework, 2) involve the right people into the project from start after clarifying their roles and responsibilities and ownership, 3) create a lessons learned portal to get immediate help in future endeavors, if required, 4) eliminate the need of duplicate efforts in releasing the information in two different systems. Basically, it was found that the development time will be reduced further when requirement of other system is removed and the power user needs to release the information only one time.

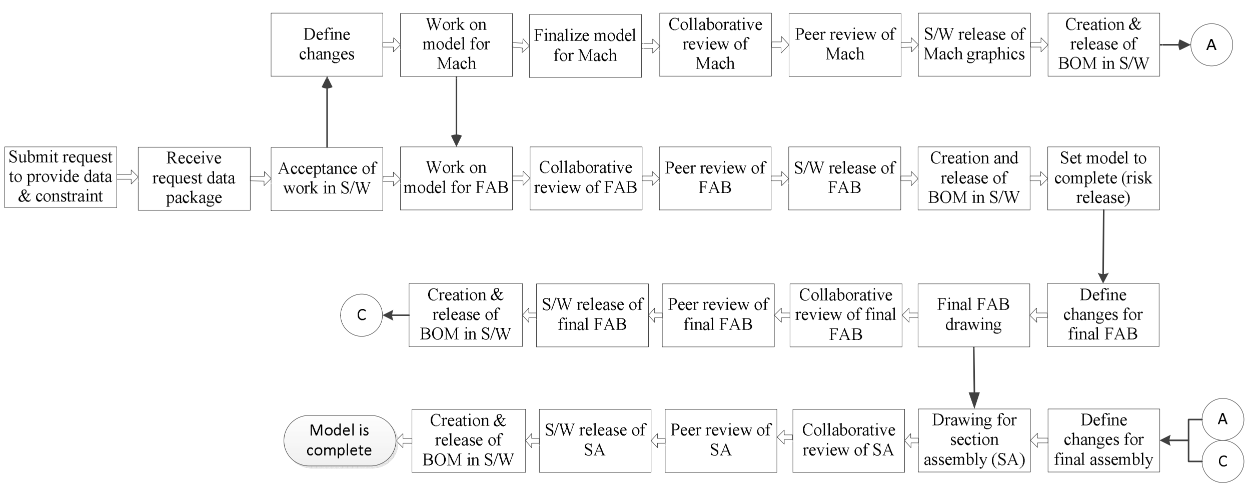

Figure 8: Future State Map (Modified)

2.5.1.2 Future state analysis

Future state map demonstrates the output of the proposed changes based on the gaps identified in the snapshot of the "as-is" state of the current state. It was asked to involve the supplier earlier in the process to have a high degree of correct information and coordination. It should be achieved by improving communication upfront to foster proper information regarding product and process. This will bring the necessary knowledge to execute the steps in correct manner eliminating the need of rework through iterations at back end of the process. It will also help the involved departments to understand and share same vision for future products.

Table 3: Comparison of data for current state and future state and improvement

Number	Criteria	CS values	FS values	Changes
1	Total number of steps	48	29	19
2	Number of value added steps	10	15	5
3	Percentage of value added steps	25%	52%	27%
4	Total time in system	620 days	210 days	410 days
5	Value added time	122.5 days	122.5 days	0
6	Percentage of value added time	21%	71%	50%
7	Total waiting time	272 days	30 days	242
8	Total number of hand-offs	87	23	64
9	Total number of iterations	17	8	9
10	Number of software involved	11	9	2

As can be seen from Table 3, a 30% increment in value added steps due to removal of waste steps is achieved. The percentage of valued added time is increased from 21% to 71% (50%). This increase is mainly due to improvement of value added steps in PDP. Waiting time is reduced from 272 days to 30 days. There is also a significant decrease in the total number of hand-offs from one department to another department for many iterations (from 87 to 23). Supplier involvement from the beginning reveals to be the main reason to reduce so many handoffs. Therefore, early involvement in the team meetings will reduce the uncertainty in the beginning of the design phase. A final decision could be reached through meetings as compared to making multiple changes later. The total number of iterations is also reduced to 8 from 17.

Although, improvement ideas induced from VSM session are still in the implementation phase, there are numerous expected benefits once all the proposed ideas are implemented. Mainly, there will be a continuous focus on elimination of enormous amount of non-value added activities (multiple reviews, multiple approvals, multiple handoffs, waiting times, reworking designs etc.) leading to the reduction of product development time by more than 50%. It transform the culture from “firefighting” to a “problem solving” one increasing the flow of communication across the organization (enforce the discipline). It will also shift the attitude of employees towards surfacing problems and treating them as opportunities for improvement. Quick access to relevant, complete, correct amount of available knowledge without waiting escalates the dispositions resulting to improved efficiency of individuals. Finally the organization will be able to witness some intangible benefits including an enhancement in respect for culture, identity, and relations among the employees.

Even though there are evident benefits of VSM, the end user should be careful while working. VSM can be misleading for the decision maker if the current state is not captured preciously at any given time to understand the situation. In addition to this, VSM just provides the situation to explore the areas which need immediate attention for improvements. It basically does not provide any direct solution of the issues. Irrespective of both these limitations, it is a substantive concept liking tools and people allowing everyone to empathize and improve continuously regarding understanding of lean and their organization.

2.6 MANAGERIAL RELEVANCE

Recent business trends in the competitive environment have shown that profits of a company are shaped by price and lead-time decisions (Pekgun 2007). More than half of the total expenditure is spent on wastes during PD which takes around 4–5 years for under study company ABC (Liker 2004; Kennedy 2008). With this regard, the contribution of this chapter is three-fold. First relevance is to change the mind-set of employees by reorienting their thinking around the Lean philosophy. Once the employees will start to live the lean culture, the organization will start to realize more the emerged benefits (long term advantage). Second contribution is to provide a step by step approach in form of a systematic framework to the implementation of lean thinking tools in a PD. This systematic framework can be further modified, customized, or tweaked to implement tools to other efforts in same or different research domain. The third relevance is to improve the competitive position through wastes reduction in a PD environment to make the existing PD process leaner. This waste reductionist approach assists in reducing the lead-time and achieving cost targets with competitive advantage (short term benefit).

CHAPTER 3. LEAN TOOLS AND METHODS TO SUPPORT EFFICIENT KNOWLEDGE CREATION

3.1 INTRODUCTION

An organization must compete vigorously to thrive in the current dynamic and demanding marketplace. This requires regular enhancements in the critical attributes to develop a superior product at a cheaper cost (Cai and Tyagi, 2104). Continuous innovation and the knowledge enabling such innovation play an important role in achieving the aforesaid goals (Esterhuizen et al., 2012). Knowledge Bridge Consulting reported in a survey that organizations consider knowledge management as an innovation booster to adequately answer the market niches. A knowledge management system institutionalizes knowledge into databases or repositories. In this context, the vast knowledge management literature primarily focuses on how to capture, sort, store, locate, or retrieve knowledge to achieve internal competitive advantage (Davenport and Prusak, 1999; Cortada and Woods, 1999; Alavi and Leidner, 2001; Nevo and Chan, 2007; Ardichvili, 2008; Liebowitz, 2009; Date and Sinha, 2013). The capability to archive lessons-learned and best practices in a knowledge management system is a pre-requisite, but does not suffice in achieving the aforesaid organizational goals. This is owing to the fact that knowledge in a computerized knowledge management system is not refreshed regularly in the western companies. The occurring changes are only related to adopting an advanced information technology (IT) tool. IT tool predominantly strives to manage the explicit knowledge and overlooks the need for creating, updating, and utilizing new knowledge, strong practices, tools, or methods (Morgan and Liker, 2006). This forces product development engineers to rely on and exploit the same old obsolete and inadequate knowledge, which results in incompetent products. Therefore, a focus on capturing knowledge that already exists through a new knowledge management scheme can prove to be another futile attempt towards innovation (Johannessen and Olsen, 2010).

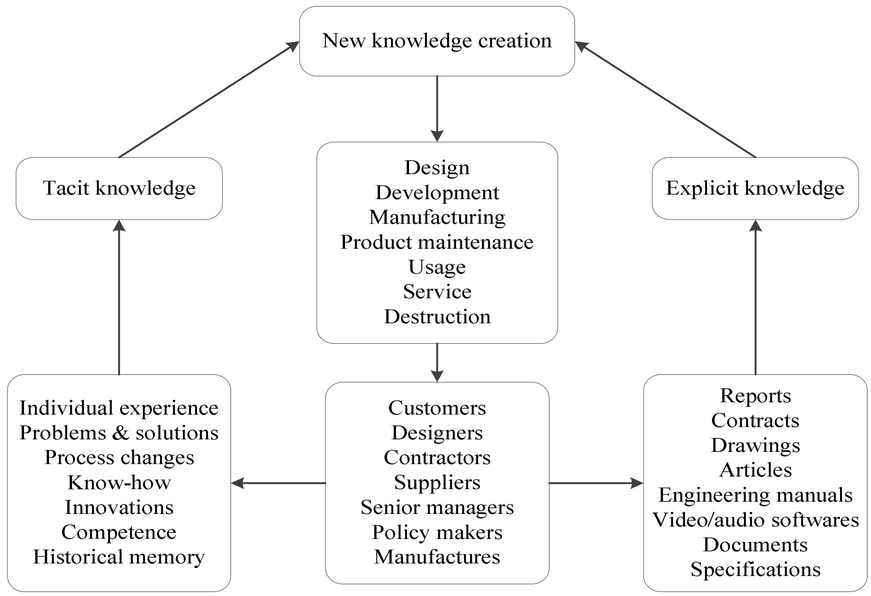

Figure 9: Schematic representation of knowledge creation in real world

Indeed, it cannot be denied that increased internal efficiency is probably associated with the initiatives pertaining to capturing, storing, accessing, and transferring existing knowledge. But both academics and practitioners consider external growth to be the outcome of dynamic knowledge (Madhavan and Grover, 1998; Popadiuk and Choo, 2006). This has resulted in the development and adoption of various knowledge creation models in practice. These models provide details on how to create, transfer, and reuse knowledge of products, processes, and customers. This chapter mainly focuses on an integrated dynamic knowledge model, which is comprised of: the SECI modes, the 'ba' (shared context), and the knowledge assets. The model predominantly illustrates how to facilitate knowledge creation and manage the way it is shared. Knowledge creation occurs continuously; for example, knowledge possessed by designers about designs in the form of explicit (reports or drawings) and tacit knowledge (experience or know-how) helps in creating knowledge when these designers come in contact with other partners such as contractors or policy makers. Their interplay results in a new knowledge which is exploited to develop an improved design. Figure 9 schematically represents the knowledge creation during the product development life-cycle in the practical settings.

Implementation of lean tools and methods inadvertently initiates and supports knowledge creation activities. A product development team should exploit this knowledge to shorten development cycles and reduce the large costs of unplanned loop-backs. But pragmatic studies where customized lean tools and methods implemented in product development for the aforesaid purpose are lacking. This lack of studies may be due to the reasonable success of a company just by improving operational systems and understanding of lean as only a tool to eliminate waste (Tyagi et al., 2014). Considering lean as a method only to identify and eliminate wastes creates a gap between the ways knowledge creation practices are performed in the real world. This chapter is an attempt to bridge this gap. Barring the research work of Kennedy et al. (2008), Morgan and Liker (2006), and Lindlöf et al. (2012) which focused on implementing lean tools for knowledge sharing and learning in a product development environment, studies that integrate lean thinking in dynamic knowledge research are still absent in the literature. The expected contributions of this chapter are two-fold. This study sheds light on how the product development domain of an organization creates, maintains, and reuses dynamic knowledge using the integrated model. From this aspect, the first contribution is to explicitly present the advanced model of knowledge creation for product development domain and to establish its superiority. Second, the goal is to establish a relationship between the integrated model and lean thinking, and then to analyse the proposed ten tools/methods with a view to support and improve the efficiency of a knowledge creation process. Hence, this study looks beyond traditional knowledge management by focusing specifically on knowledge creation in a product development environment.

3.2 LITERATURE REVIEW

Elusiveness in specifying the definition of knowledge presents the considerable challenges in conducting the research (Schultze and Stabell, 2004). The work of Kane et al. (2006) emphasized this and offered a prominent but conflicting definition of knowledge. Simply put, knowledge is what one already knows, and knowledge management is the practice of making that knowledge instantaneously available in a usable format to create value. After defining “knowledge,” a more fundamental need is to understand how successful organizations create knowledge that makes innovations possible. Knowledge creation is defined as the process of continuously updating or increasing the knowledge base of what one knows now, rather than what one didn’t know before, and keeping it accessible, and usable. The basic difference between knowledge management and knowledge creation is that the former helps in filling the gaps to obtain raw data or information but latter actually assists in problem solving. Moreover, interactions among internal and external resources can be leveraged to generate knowledge from existing knowledge unlike other inert resources (Leonard and Sensiper, 1998). Yet, research papers drawing attention to opportunities and limitations specifically related to knowledge creation are comparatively few (Yang et al., 2010). Alavi and Leidner (2001) and Liu (2012) asked essential and interesting research questions related to the conditions that facilitate knowledge creation, incentives that encourage knowledge contribution, and support that triggers effective knowledge transfer among organizational units.

Towards this end, the literature describes numerous state-of-the-art dynamic knowledge models such as Nonaka (1994), Boisot (1999), Nonaka et al. (2000), Nissen (2006), and Martin-de-Castro et al. (2008). The SECI model proposed by Nonaka (1994) is considered the most influential and is universally accepted. This model entails activities to create knowledge, and disseminate it within an organization. Afterwards, Boisot (1999) exploited the "Theory-of-Information" to develop the 'I-Space' conceptual framework, which consists of three phases: codification, abstraction, and diffusion. This model is not comprehensively applicable in practical settings, and remains an abstract and complementary tool suitable for understanding knowledge dynamics. Further, the concept of knowledge flows in the dimensions of time and space inspired Nissen's model of knowledge dynamics (Nissen, 2006). The difference between knowing and understanding is the main driving force for the knowledge flow and corresponds to the emitter and receiver in physics. However, Nissen (2006) failed to discuss core constituents like the knowledge gradient and the process of knowledge flow. Martin-de-Castro et al. (2008) proposed an Epistemological– Ontological (EO)-SECI knowledge creation model, which is an extended version of the SECI model of Nonaka (1994). This model is most useful when it is used to demonstrate knowledge dynamics in a knowledge intensive environment. Drawing on prior work, Nonaka et al. (2000) further extended the basic SECI model by unifying two more elements: 'ba' and knowledge assets, with SECI, where 'ba' is a physical, virtual, or mental space of shared aspects where knowledge is generated. Among all, the integrated dynamic knowledge model proposed by Nonaka et al. (2000) is the most advanced and hence has been targeted in this research. Details of this model are provided in section 3.

Next, the applicability of lean tools and methods that can improve the efficiency of a knowledge creation process in the integrated dynamic knowledge model proposed by Nonaka et al. (2000) is investigated in this research. Authors such as Oppenheim (2004) and Locher (2008) offered lean product development (LPD) as a method to identify and eliminate wastes similar to lean manufacturing. On the contrary, LPD has also been explained as a method of capturing, transferring, and using/reusing knowledge (Ward, 2007; Kennedy et al., 2008). Hines, Francis, and Found (2006) provided a framework to understand the evolution of lean from conceptual and implementation aspects of organizational learning. Kennedy et al. (2008) concentrated on the importance of knowledge by separating product flow and knowledge flow. The former derives short term benefits by delivering products ready to be produced and sold, whereas the later aims to build knowledge about technology, customers, and processes for the long term gains. Few works encountered in the literature have also analysed the basic SECI model in a product development environment. Hoegl and Schulze (2005) presented a set of non-lean practices to support knowledge creation without particularly considering the SECI model. Madhavan and Grover (1998) and Schulze and Hoegl (2006) compared the SECI modes with product development phases to advocate its importance in the performance improvement analysis. Bratianu and Orzea (2010) critically analysed the SECI model by applying entropy laws to understand the conversion process and then presented characteristics of other models to compare with it. Andreeva and Ikhilchik (2011) presented a theoretical model to analyse the applicability of the SECI model in a Russian culture context. They basically discussed the model and challenged the mainstream assumptions of universal applicability. Easa (2012) discussed the methodological aspects to examine the applicability of the SECI model in knowledge creation and its effects on innovation in Egyptian banks. Frank and Echeveste (2012) proposed knowledge transfer among development teams as a method to identify improvement opportunities without considering SECI model. Lindlöf et al. (2012) studied LPD from SECI relevance within a product development environment. Further, Murphy and Salomone (2013) used social media to facilitate knowledge transfer in complex engineering processes. Despite all aforesaid focuses, the literature review did not reveal any particular study that put the lean thinking in the context of knowledge creation research. The past literature primarily targeted knowledge transfer process as a part of knowledge creation process. The authors were motivated predominately by the research work of Hoegl and Schulze (2005) and Lindlöf et al. (2012). Hoegl and Schulze (2005) proposed a set of non-lean tools to support knowledge creation without focusing on how knowledge creation happens in the SECI model. Further, Lindlöf et al. (2012) primarily focused on knowledge transfer only and analysed limited LPD tools in the context of the basic SECI model. Frank and Echeveste, (2012) and Murphy and Salomone (2013) also discussed the knowledge transfer with in the product development domain for different objectives without considering on any particular process.

This research attempts to address the aforesaid gaps that are encountered in the literature. This dissertation extends the research work of Lindlöf et al. (2012) and discusses an advance form of SECI model from knowledge creation perspectives and analyses a more number of lean tools/methods to improve the efficiency of knowledge creation process. No study in the literature, to our best knowledge, targeted the application of various lean tools and methods to improve the efficiency of an integrated dynamic knowledge model. The underlying proposition behind this is: the quality of products delivered by a firm is directly proportional to the efficiency of knowledge creation. Consequently, this dissertation goes beyond a large and growing literature on knowledge management to address the challenges of knowledge creation in supporting product development. This study proposes a comprehensive list of lean and non-lean tools and methods in an implementation framework. This research focuses on the processes that employees perform during their daily activities, and considers them from a knowledge creation perspective. The present model offers a general implementation which can be extended to other sectors such as services and marketing. An integrated dynamic knowledge model to illustrate practical knowledge creation is detailed in the next section.

3.3 INTEGRATED DYNAMIC KNOWLEDGE MODEL

Existing knowledge within an organization may be exploited in dealing with problems by exploring, defining, and developing their solutions. During this problem solving exercise, teams not only take actions to solve them, but they also gain the dynamic knowledge (Figure 10). Both environment and organization interacts with each other and absorbs the required changes through knowledge creation. Here knowledge is being created (instead of just processing the information) through a nexus of interaction between team members, problem solving actions, and tasks performed. Therefore, knowledge creation follows a spiral shaped path by oscillating between sharply contrasted concepts such as order and chaos, micro and macro, part and whole, mind and body, tacit and explicit, self and other, and internal and external. Nonaka et al. (2000) presented an argument that such dialectical thinking plays an important role in transcending and synthesizing contradictions, which ultimately leads towards dynamic knowledge. An organization can possess a stock of knowledge, such as technology, which may become irrelevant in the future. Gained new knowledge and its application is the major resource for an organization's survival. Therefore, dynamic nature of knowledge is the prominent force for realizing the strength of an organization.

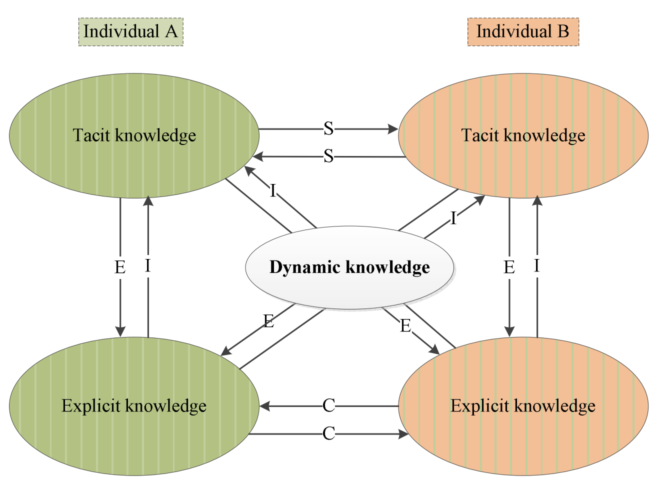

Figure 10: Linear representation between two individuals A and B

3.3.1 SECI modes

According to Nonaka et al. (2000), knowledge is divided into two types: explicit knowledge and tacit knowledge. Explicit knowledge can be presented in the form of a code, in language, and in written reports using data, scientific formulas, and manuals. Therefore, it can be communicated, processed, transmitted, and stored relatively easily. On the other hand, tacit knowledge refers to knowledge, which is only known by an individual and is difficult to communicate to the rest of the organization. It is personal knowledge embodied in actions, attitudes, commitments, emotions and behaviour, and is difficult to codify sufficiently to communicate in a 'language.' It can only be learned by sharing experiences, and by observation and imitation (Hall and Andriani, 2002). Facts and theories—i.e. 'knowing-about,'—fall under the category of explicit knowledge, whereas skills to perform any task or job, 'knowing-how,' are in the realm of tacit knowledge. It is very difficult or nearly impossible for anyone to learn and develop 'know-how' skills just by reading or by watching audio/video media. The individual has to indulge in the hands-on experience in order to gain tacit knowledge. Among the two, tacit knowledge is more important owing to its "know-how" contribution towards continuous innovation.

Although tacit knowledge is a source of competitive advantage, it quickly loses its meaning without explicit knowledge. They complement each other and the absence of one undermines the power of the other. Nonaka et al. (2000) stated that their (tacit and explicit) interplay is required for dynamic knowledge. The four-stage spiral model abbreviated as SECI modes is used to depict four separate modes: socialization, externalization, combination, and internalization. The beginning point of this spiral is socialization, where the exchange of tacit knowledge at the individual level is used, without specifying any particular language, to create knowledge. For example, children imitate the behaviour of their parents and learn from it. This is followed by an externalization mode where tacit knowledge is transformed into explicit knowledge to create knowledge. Written reports coming from lessons learned and impressions from experiences are examples of externalization. In combination mode, dynamic knowledge is gained by pooling isolated and existing pieces of explicit knowledge into a holistic system structure. The final mode of spiral is internalization, where individuals absorb this new explicit knowledge. Explicit knowledge is applied multiple times, enriching the tacit knowledge base by including it in habits and daily routines. The knowledge creation cycle continues along the spiral and jumps from the individual level to the organizational level when tacit knowledge is exchanged again. The SECI modes must be supported by two other elements-'ba' and knowledge assets-to realize knowledge creation as shown in Figure 11 (Nonaka et al., 2000).

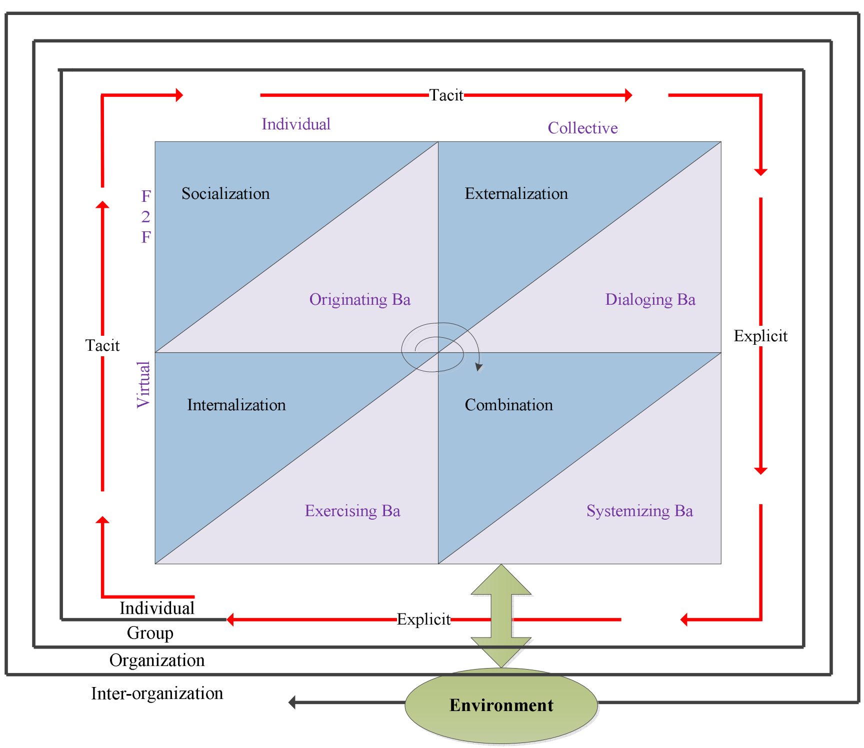

Figure 11: Integrated dynamic knowledge model in a spiral form

3.3.2 ‘ba’

Knowledge creation or sharing cannot occur in a vacuum, instead depends on the method of participation and the individuals who participate. The Japanese philosopher Kitaro Nishida introduced the ‘ba’ concept and Shimizu later refined it. The Japanese word ‘ba’ refers to a specific time-space nexus, and conceptually unifies physical space, virtual space, and mental space such as an office space, e-mail, and shared ideals. ‘ba’ means the place, and in current jargon it’s the zone that actively supports simultaneous and spontaneous interaction in parts or in whole for knowledge creation. It also provides a shared context for the meaningful existence of knowledge and bridges the gap with information (Nonaka et al., 2000). The context changes the meaning of knowledge, when shared or interpreted for a purpose. The shared context or place can be tangible, intangible or a combination of both to create and utilize the knowledge. Commitment to spend time and energy on events as well as in activities and interactions in ‘ba’ is very important for knowledge creation.

Interaction level (individual or group) and media type (face-to-face or virtual) result in four types of ‘ba’: originating, dialoguing, systemizing, and exercising (Nonaka et al., 2000). In originating ‘ba,’ individuals share experiences and feelings face-to-face. Dialoguing ‘ba’ is helpful in promoting face-to-face interactions among group participants. Systemizing ‘ba’ offers a combination of explicit knowledge in virtual space through a group interaction. The members participate and engage in various ‘ba’ to develop a shared sense of purpose by interacting with each other, and transcend one’s limited and subjective perspective to create knowledge (Nonaka et al., 2000). The individual’s interaction in virtual space falls under the category of exercising ‘ba.’ ‘ba’ lays a foundation of four SECI modes for informal, simultaneous, and dialectical dialogues among individuals and/or a group in physical and virtual space, as shown in Figure 11.

3.3.3 Knowledge assets

The knowledge assets depend heavily on the strategic orientation of a firm and the characteristics of 'ba.' They are intangible firm-specific resources such as inputs or outputs of the knowledge creation process that contribute in yielding value. Existing know-how skills, patents, and technologies are in the category of already acquired knowledge assets. They have received a lot of attention due to their tangible attributes and relative ease in measuring. However, knowledge creation is an organizational capability and a source of innovation that needs attention (Nonaka et al., 2000). A specific way of doing things is reflected in one of the most important knowledge assets termed “kata.” It consists of three simple steps: shu (learn), ha (break), and ri (create), which is a dynamic thinking pattern intended to create a self-renewal process. The thinking pattern of the firm is a continuous process changing obsolete sources of knowledge to new ones for a successful future. Such knowledge assets cannot be evaluated and managed effectively, owing to the lack of effective systems and tools. It is nearly impossible to buy or sell the organizational knowledge assets, so they must be built within. A high level snapshot of presently owned all knowledge assets will not be enough for managing them properly in the future. Therefore, Nonaka et al. (2000) divided knowledge assets into four types: experiential, conceptual, systemic, and routine, in order to understand how knowledge assets are created, acquired, and exploited. The next section highlights the role of lean thinking in product development.

3.4 LEAN THINKING IN PRODUCT DEVELOPMENT

The Toyota Production System built on lean thinking is the most successful disruptive innovation after Ford’s River Rogue plant (Ohno, 1988). The term “lean thinking” was first coined by Womack et al. (1990) in their famous book "*The Machine That Changed the World.*" Later, Womack and Jones (2003) proposed the five lean principles, which are (1) specify value, (2) identify the value stream and eliminate waste, (3) make the value flow, (4) let the customer pull (value), and (5) pursue perfection. In essence, leanness mainly depends on one critical starting point called "value" that can be defined only by the customers. Hence, lean tools and methods primarily focus on exploring ways to identify and eliminate the seven deadly wastes that add no value for a customer or an organization (Liker, 2004; Cai et al., 2011). Their implementation, particularly within manufacturing operations has turned out to be an enduring domain of earlier research (Khalil and Stockton, 2010). McManus (2005) stated that a tested theory that puts lean thinking into the heart of a holistic system and has the ability to extend across other elements of an enterprise, such as product development, is still rarely mentioned in the literature. This is owing to the inherent differences between manufacturing and product development. Therefore, it is worthwhile to compare the two to notice the distinctions (see Table 1). For example, in the former, loopbacks are associated with wastes and considered to be a diminishing contribution; however in the latter, loopbacks could be associated with gaining important dynamic knowledge. Hence, direct implementation of lean principles from manufacturing to product development is questionable and full of doubts (Radeka, 2012).

This gap has been identified as a potential area of research by a number of authors. Morgan and Liker (2006) and Ward (2007) provided different perspectives to compare manufacturing and product development and stressed that lean tools and methods have the ability to be modified appropriately to work well in latter. For example, in manufacturing the "pull" principle focuses on eliminating overproduction of material. This is done by maintaining a balance in demand from downstream activities to supply of upstream activities using signals adding a value for the end-customer. Similarly in product development, knowledge is pulled/ created to get the right information to the right person at the right time. Most lean tools and methods inherently support knowledge creation in one or multiple SECI modes. Generally, organizations tend to neglect the long-term benefits as they target only such short-term benefits of bringing products to the market faster (Kennedy et al., 2008). Morgan and Liker (2006) mentioned several lean tools and methods for standardization and visual communication that can also assist effective and powerful knowledge creation. Organizations are required to adapt those tools and methods to fit their people and specific culture. Moreover, tools and methods that support knowledge creation are not necessarily lean, so this research also introduces some non-lean tools and attempts to integrate them in the daily work. It helps employees to accept their implementation with higher efficiency and enthusiasm. The next section describes the methodology used in this research.

3.5 RESEARCH METHODOLOGY

Seven different perspectives to understand LPD are performance analysis, decision-making, process-modelling, strategy development, supplier partnership, lean manufacturing, and knowledge networks (Martinez et al., 2011). In knowledge networks, generally, the SECI model (Nonaka, 1994) has been exploited to develop knowledge-related research frameworks. However, important points like input/output of a SECI mode or physical/virtual space where the knowledge is created or shared have been neglected. In order to tackle this, an integrated dynamic knowledge model proposed by Nonaka et al. (2000) that is comprised of three elements: SECI modes, 'ba' and knowledge assets, is targeted. This model is adopted since it is the most advanced model that clearly exemplified how knowledge is created in practical settings. This dissertation discusses the implementation of ten lean tools and methods in the integrated model to enhance the efficiency of knowledge creation in a product development domain. In the literature, researchers and practitioners have identified, analysed and documented a large number of lean tools, methods, and techniques based on Toyota Production System. For authors, it is important to understand how they can specifically address the needs of knowledge creation. The key is in picking the right mix and integrating them into the strategy to deliver the most value; otherwise they will end up resulting in a lot of waste. Experts like Ward (2007), Morgan and Liker (2006), Kennedy et al. (2008) and the relevant research papers available in literature agreed upon 21 LPD enablers. All of them can be considered as the ingredients of the LPD framework. Among the 21 agreed-upon LPD enablers, however, this dissertation proposes a set of 10 lean tools and methods which perfectly fit for implementation in integrated dynamic knowledge model. These items were selected based on a consensus of researchers and practitioners known for their expertise and experience in product development domain. These tools and methods are: 1) apprenticeship, 2) employee cross-training, 3) the chief engineer, 4) set-based concurrent engineering, 5) trade-off curves, 6) visual tools, 7) checksheets, 8) scrum, 9) PDCA, and 10) the 5 whys. In section 6 below, each of them is analysed and appropriately positioned in a SECI mode depending on best fit and support for knowledge creation. The rationale behind selecting an appropriate SECI mode for each lean tool/method along with potential 'ba' and knowledge assets are explained later in the implementation analysis section. Concentrating on deploying a large number of lean concepts can result in negative feedback from employees in terms of utilization. This is due to the fact that employees have to possess or learn an adequate understanding of each concept and a higher number of lean tools can draw less interest and lack of usage, which can lead to their banishment in the future. So the optimal number of lean tools/methods should be enforced to realize the maximum benefits. Once those tools/methods are implemented, gradual and continuous improvements should occur in them. At the same time an organization should explore, develop and encourage more tools/methods. In the next section, each of them is briefly introduced to keep up with the objective of this dissertation.

3.6 IMPLEMENTATION ANALYSIS

Two branches of research are theoretical analysis and empirical analysis, and the order in which they are linked with each other defines two research strategy types. The deductive strategy that focuses on "theory–then–research," and the inductive strategy that follows "research–then–theory,'' have been recognized in the literature as appropriate (Yin, 2009). This dissertation employs a deductive strategy in analysing lean tools/methods to support efficient knowledge creation and bridge the research gap. An overview of the analysis is as follows. For Socialization, apprenticeship, informal meetings and employee cross-training are discussed. Under Externalization, the chief engineer, set-based concurrent engineering, and trade-off curves are analysed. For Combination, two visual tools (A3 reports and spaghetti diagrams) are explored. For Internalization, two visual tools (A3 reports and virtual obeya) and the use of checksheets are discussed. Finally, three tools: Scrum, PDCA, and the 5 whys, are shown to support knowledge creation in all modes.

3.6.1 *Socialization mode*

According to Oshri et al. (2007), the socialization mode offers an opportunity for experience sharing to create tacit knowledge and improve collaboration throughout a project life-cycle. It encourages individuals to spend time together in joint hands-on experiences, informal meetings, and work in the same environment to exchange personal or specialized knowledge (Li et al., 2009). Socialization requires the trust, respect, and mutual understanding among resources during the course of communication. This helps in combining a comprehensive form of tacit knowledge to enrich ‘sympathized knowledge,’ such as an intellectual model and technological expertise (Nonaka and Takeuchi, 1995). The required ‘ba’ for the socialization mode is face-to-face interaction locations, video conferencing tools, and virtual reality tools. The shared context of learning from apprentice and coaching from the leader is another required ‘ba’ for successful knowledge creation. The knowledge assets for socialization mode are know-how and skills possessed by individual employees regarding the current products, processes, customers, suppliers etc.

3.6.1.1 *Apprenticeship*

Apprenticeship goes against the orthodox approach that believes in ‘command and control’ (Evered and Selman, 1989). The traditional way of micromanagement does not offer an ambiance conducive to gain tacit knowledge, and thus does not help either the coach or the apprentice. On the contrary, lean thinking encourages a leader to patiently coach the apprentice who learns by doing under his/her direct supervision. This is due to the fact that mentors (leaders) naturally possess a vast amount of experience in the form of tacit knowledge, and are experts in their domain (Verma et al., 2014). Apprenticeship requires a strong desire to communicate and interact with others by engaging in day-to-day hands-on activities. Adoption of this approach can influence how a company allows individuals to share experiences, intuitions, observations, and imitations. For example, in Toyota a new employee is assigned to a leader who works with the junior employee as a mentor for strict training and development. New employees are advised to do their jobs under the guidance of a leader to focus on methods rather than results and learn them (Morgan and Liker 2006). In the game of cricket, the Australian Cricket Board management has assigned individual current cricketers with former expert players based on one’s talent and abilities. It helps an individual player to hone one's skills under proper guidance. This is another example of apprenticeship and exemplifies the interpersonal creation of tacit knowledge through socialization.

3.6.1.2 *Informal social activities*

Encouraging social activities outside the work place for direct and face-to-face communication empowers teams to gain new insights. Leonard and Sensiper (1998) stated that comfortable communication of tacit knowledge is only possible if there is a mutual trust and understanding. They are nurtured by facilitation of social interaction and networking. Organizations should initiate and encourage informal internal events providing an extended interaction for employees to share ideas and perspectives. Social interactions among individuals lead to more accurate interpretations, as compared to when individuals decipher information alone (Alavi and Leidner, 2001; Tyagi et al., 2011; Tyagi et al., 2012). Establishing such dialogues can pave the way for improved performance of the development projects.

3.6.1.3. Employee cross-training

Most organizations have already recognized that employees are their most important assets. Investment to augment the capabilities of an asset is important, and leadership must promote, encourage, and actually become involved in this. Training and education to bring deliberate changes is the primary driving force for dynamic knowledge that benefits both employer and employee. Such training helps a team member to perform a wide range of activities enhancing flexibility and greater idea generation capabilities. Employees with greater flexibility and capability can open a new horizon for an organization to offer quality products and services. On the other hand, for employees cross-training provides an opportunity to gain dynamic knowledge and skills, increasing their value, positively impacting their confidence. It also helps the employees to attain enrichment and enlargement in terms of their jobs.

Other potential methods that can likely improve knowledge creation during the socialization mode are involving cross-functional teams in joint projects, arranging meetings, seminars, and training workshops, lunch and learn sessions with other departments, inviting qualified members and external experts to speak about their beliefs, values, and culture, and providing a common place for lunch breaks or other activities, technical speed dating, monthly cascade meetings etc.

3.6.2 *Externalization mode*

Researchers are still trying to identify the key influencers, which can mitigate the difficulties of the socialization mode. This shifts the focus towards externalization where best practices and lessons learned are documented to avoid high uncertainty in future innovation (Gold et al., 2001). Knowledge is created when existing knowledge is changed from tacit to explicit form (Choi and Lee, 2002). During this mode, the know-how knowledge is exposed in the form of concepts, hypotheses, metaphors, analogies, and models for explaining in more tangible and generic forms through demonstration, comparison, and experimentation (Salmador and Bueno 2007). An organization pushes externalization to create conceptual knowledge and convert abstract ideas into a concrete form of information through text and symbols. A high commitment and participation of internal qualified members and external experts in the training programs and seminars with little external control (little pressure from shareholders) are required for successful completion of externalization. Open dialogue among employees and senior leadership who are seeking honest feedback is a strong motivation for reducing ambiguities. The potential ‘ba’ for externalization are interview rooms, Microsoft productivity tools such as Word and PowerPoint, tools to capture processes, expert systems, discussion platforms such as meeting rooms, and reflective peer-to-peer networks. The knowledge assets are images, languages and symbols of product concepts, designs, and brand equity.

3.6.2.1. *Chief engineer*

The Chief Engineer (CE) is one of the most important lean methods. This position acts as a “heavyweight project manager” who exerts the total responsibility for multiple development projects to timely drive them with a view to achieve aggressive targets (Morgan and Liker, 2006). In addition to the development projects, the CE puts forth strenuous efforts to understand customer values and needs during the socialization mode (Ward, 2007). Morgan and Liker (2006) also emphasized that the CE is someone who promotes knowledge externalization. Once the needs of the customer are understood, the CE communicates them through concept papers and other communication approaches to other team members. In such papers, the CE externalizes the tacit knowledge in the form of explicit knowledge; thus, allowing others to obtain and grasp it and act upon it.

3.6.2.2. Set-based concurrent engineering (SBCE)

SBCE encourages designers to consider a broad range of potential alternative concepts in the beginning, instead of a single solution as in point-based engineering. Cross-functional teams including market analysis, design, development, testing, and manufacturing contribute by providing information in parallel to help develop alternative design concepts. Subsequently, concepts converge by deleting weak designs attributes until a superior solution is found. The objective is to eliminate wastes early in the product design process so that the need for costly design and engineering changes at the back-end is minimized. Fundamentally, starting with a set of design alternatives instead of a single design assists in voiding iterations and gigantic amount of rework. SBCE helps the externalization mode by capturing knowledge such as design rules from engineers and systematic evaluation of the development process. The dynamic knowledge can be stored or manipulated and can be transferred to others for future reuse. In order to investigate SBCE, Liker (2004) pointed out the example of new suspension development for the Prius car at Toyota. Toyota held a competition and got around 20 potential suspension designs to evaluate and test simultaneously, instead of using trial and error to modify a single design, to minimize the total cost of development.

3.6.2.3. Trade-off curves

Trade-off curves, considered to be a cornerstone of the externalization mode, are simple graphical representations to demonstrate the change of performance of output (X) against one or more parameters (Y). The example includes estimation of key parameters such as diameter and wall thickness of a pipe (design decisions) to match customer requirements of fluid pressure and velocity (Tyagi et al., 2007). Such curves embody explicit knowledge generated during tests and can be used in future endeavours. Succinct trade-off curves facilitate codification and generalization of knowledge of the quality issues in order to avoid them in the future. Toyota heavily relies on extensive prototyping during product development to successfully develop and release new models of a car in record-breaking time. Toyota spends a considerable amount of time and effort to develop the trade-off curves from the analysis of prototyping data. Such test data analysis knowledge in form of trade-off curves provides the ongoing knowledge for future projects, and, thus, reduces redundancy. The employees externalize the tacit knowledge through a trade-off curve when knowledge is articulated in the form of documents or experience reports. This knowledge generated through the trade-off curves is quite useful in creating standards and making intelligent decisions.

Other methods to foster externalization are conducting experience workshops, expert interviews, and experience reports. The objective of experience workshops is to take a retrospective view to share important aspects and take away learned lessons, exchange of experiences, and to judge the project's success (or lack of success) for subsequent projects. Important questions related to the objective of the project, achievements, successes/failure and how to use this knowledge in the future should be asked by an outside project facilitator. Activities that report the beliefs, values, experiences, and culture of internal and external experts are especially encouraged. However, eliciting, codifying, and transforming the Subject Matter Expert's (SMEs) knowledge into a sharable format is a painstaking task owing to dynamic attributes and the subjective nature of knowledge.

3.6.3 *Combination mode*

Time spent by SMEs on project oriented tasks is more valuable than that of writing reports (Tyagi et al., 2013). In addition, tight schedules make knowledge creation difficult in the externalization mode so manual knowledge compilation or other appropriate methods are important. In order to maintain expertise or technological knowledge for a longer period at the enterprise level, another knowledge creation mode seems essential. Collected reports issued by the internal and external agents (e.g., customers, competitors, partners, or government representative) are integrated, classified, reclassified, and synthesized with various existing explicit notions possessed by employees, to form a cluster of organized knowledge resulting in 'systemic explicit knowledge'. In this mode explicit knowledge mentioned in files, databases, networks, and reports is classified and transformed into intricate and organized explicit knowledge to identify innovative products or technologies most likely applicable to be put into practice. The potential 'ba' for the combination mode would include tools for systematizing knowledge, tools for collaborative computing, web forums, best practices databases, lists for discussion, and the intranet. The knowledge assets are systemized and packed documentation, manuals, specifications, database, patents and licenses.

3.6.3.1 Visual tools

Visual tool boards are a powerful way to create knowledge during the combination mode. A3 reports and spaghetti diagrams are two main examples of visual tools considered in this research. An A3 report is only a single piece of A3 size paper that contains graphs and visual representations instead of large texts. Engineers synthesize, distil, and visualize the knowledge to put a large amount of both tacit and explicit knowledge into compressed form (Sobek and Smalley, 2008). They epitomize the old adage, "one picture is worth 1000 words," and make it easy for the user to comprehend the information. It helps in integrating and combining old explicit knowledge with new explicit knowledge, thus belongs to the combination mode.

A spaghetti diagram is a tool that indicates the value added and non-value added workflows using a continuous line in visual flow chart format. Traditionally, the lines are hand drawn and follow the workflow during observations. These lines may not be to the exact scale of the actual process. This is because the intention of the tool is to depict the flow of work or material in order to identify and eliminate any non-value-added movements. Improved knowledge creation in combination mode is supported by creative applications of computerized communication networks and large scale databases (Nonaka and Takeuchi, 1995). These activities should be integrated with the deployment of good and proven practices or procedures, updating files, databases and website, relevant published research and reports to develop new policies. It becomes a powerful tool when it is used with 5S initiatives (5S refers to a workplace organizational methodology based on: sort, systematize, shine, standardize, and sustain). The collected information should be referenced when developing rules, reports for decision-making.

Other practices that can be helpful in combination mode are project briefings, knowledge brokers, databases, and selection of best practices. Project briefings can aid by involving the experienced team to provide knowledge and documents containing issues/results from previous projects. The new requirements can be combined with this knowledge by the current team. Generally, best practices can be considered as explicit knowledge if they are noted. They are proven approaches to handle repeating problems or processes effectively, and the documented information should be regarded as the major source of communications. Hence, functional specifications of new projects convoluted with explicated experiences or documents from the prior projects results in concrete knowledge creation during the SECI combination mode.

3.6.4 *Internalization mode*

In defining the internalization mode, Vaccaro et al. (2009) state that dynamic knowledge occurs when collective explicit knowledge is transformed into tacit knowledge, updating the mental representations of individual organization members. This is generally achieved both by accessing the organization database and intranet to obtain required information, and by analysing deliverables of training programs, workshops, seminars, and conferences. Such tuned-up, combined, and structured explicit knowledge leads towards action-oriented knowledge intended to be disseminated for pragmatic use. Analysis and explanation of relevant reports issued by suppliers, competitors, partners, or government representatives can be used during the knowledge internalization mode. This mode witnesses a functional and realistic outcome for organizational performance improvement and, thus, becomes an important stage in the SECI.

Researchers also acknowledged that if deliberate knowledge creation and transfer among partners becomes costly and tedious due to knowledge stickiness, then it can have negative impacts toward internalization (Li and Hsieh, 2009). The potential 'ba' for the internalization mode includes collaborative knowledge networks, neural networks, and notes databases. The knowledge assets are the organizational culture, organizational routines, and the know-how of daily operations embedded in actions and practices.

3.6.4.1 A3 reports

A3 reports also support internalization by facilitating transformation of explicit knowledge into tacit when used as a tool for solving problems. The issues can be discussed easily if A3 reports are hung on the wall of "Obeya rooms," or wherever the meetings occur. This can be used to explain the content of related reports or documents to shape the organizational culture and point-of-view based on the available data and information. It provides a platform for effective and timely communication to reduce waiting time for decision making. A3 reports can act as a medium to demonstrate models and/or concepts using a standard report template for knowledge externalization. Expert interviews are conducted to articulate tacit knowledge pieces in the form of written documents, which mainly contain the staff point-of-views on projects and strategies. These reports contain the results of negotiation with customers, partners, and others based on cumulated experience, and findings of meetings, seminars, workshops, conferences, and training programs.

3.6.4.2 Virtual obeya

There is a scarcity of visual control systems for integrated planning, scheduling, and work that are transparent enough for making real-time decisions. It gets worse when geographically distributed teams are involved. "Obeya" is a planning and communication tool, which roughly means "big room" in English. Each team works in a physical Obeya room and regularly collaborates with other multi-disciplinary teams. Teams 'see' the process and know where and when actions need to be completed, and where problems may arise. Virtual obeya uses a digital board for enhanced collaborative work that virtually displays current status at remote locations to focus on problem solving and coordinating actions (Blankenburg et al. 2013). Responsible representatives of various functional specialties maintain the room to support effective and timely communication across multiple locations at the same time. This interactive involvement of geographically dispersed cross-functional teams effectively controls and manages a project as compared to SMEs at only one location. Virtual obeya serves multiple purposes including real time knowledge creation with coordinated efforts, on-the-spot fast and accurate decision making by involving the right players at one place. This enables easier delegation through full visualization of the work to be performed, clearer roles and responsibilities, and an important sense of team integration.

3.6.4.3 Checksheets

Checksheets are used to put the available knowledge on a sheet of paper in the standardized form to provide a better review basis for decision-making (Kennedy et al., 2008). Checksheets are a medium to put explicit knowledge in a written form for future reuse. Toyota regularly uses them to review all design decisions and ensure a minimum quality level. They act as a reminder to remember important things and are regularly updated and used. They are beneficial in improving the documentation of information, design decisions, and knowledge reuse. They facilitate documentation and visualization to increase the knowledge base and knowledge sharing, thus knowledge internalization occurs.

3.7 Tools that supports knowledge creation in four SECI modes

3.7.1 Scrum

This sub-section provides a discussion on how knowledge is created through "Scrum," and the importance of enabling 'ba.' A scrum team consists of at least the three roles: a product owner, who represents the voice of the customer, a cross-functional development team, who actually create shippable increments of the final product, and the scrum master, who keeps the scrum process moving, and who removes impediments that are preventing the development team from delivering their products. Scrum enables fast feedback, since teams execute steps in smaller cycles for continuous improvements. The scrum team interacts iteratively to become hyper-productive and stabilize the environment where the team works. This environment is the scrum team's 'ba' which must be created and transformed continuously with a view to achieve the most from it (Sutherland et al., 2009). A scrum master should facilitate the scrum process. It is the duty of the scrum master to provide the platform to create and maintain the flow of knowledge in 'ba'. All SECI modes are present in scrum. The daily scrum meeting supports the occurrence of socialization and combination modes, given the dynamics created by having the scrum team always working together to solve problems. Additionally the technical part of the post-scrum review also supports both modes. The originating and cyber 'ba' are the scrum team's location. The required documentation depends on what the team or scrum master select that supports externalization. The team and individual members gain knowledge in short cycles of sprint and scrum ceremonies to support internalization and ultimately result in development.

Table 4: List of lean tool/method supporting the knowledge generated in SECI modes

Tool/method	S	E	C	I	'ba'	Knowledge assets
1. Apprenticeship	X				Face-to-face interaction locations, video conferencing tools, and virtual reality tools	Know-how and skills possessed by individual employees regarding current product, process, customer, supplier etc.
2. Employee cross-training	X					
3. Chief engineer		X			Interview rooms, tools to capture process, expert systems, discussion platforms such as meeting rooms, and reflective peer to peer networks	Images, languages and symbols of product concepts, designs and brand equity
4. Set-based concurrent engineering		X				
5. Trade-off curves		X				
6. Visual tools					Tools for systematic knowledge, tools for collaborative computing, web forums, best practices database, list for discussion, intranet	Systemized and packed documentation, manuals, specifications, database, patents and licenses
6.1 A3		X	X	X		
6.2 Spaghetti diagram			X			
6.3 i-Obeya				X	Collaborative knowledge networks, neural networks and notes database	Organizational culture, organizational routines, know-how of daily operations embedded in actions and practices.
7. Checksheets				X		
8. Scrum	X	X	X	X	Individual or Combination of above stated 'ba,' depending on the mode.	Individual or combination of above stated assets, depending on the mode.
9. PDCA	X	X	X	X		
10. 5 Why's	X	X	X	X		

3.7.2 Plan–Do-Check-Act cycle

The four steps of continuous improvement: Plan, Do, Check, and Act, can be viewed as the counterparts of the four SECI modes. The Plan step corresponds to socialization since there is an interaction to clearly explore the customer's objectives and the methods required to achieve those objectives. The Do step is similar to externalization when an improvement team tests solutions to the problem at hand and dynamic knowledge is generated in forms of reports, tools, and manuals. Trade-off diagrams and set-based concurrent engineering tools are generally used to conduct the testing to find the optimal solution. Thereafter, appropriate actions when knowledge is combined with existing knowledge to create knowledge ensure the success of Check-step. The Act step requires taking actions and implementing suggestions for improvements, resulting in internalization of explicit knowledge.

3.7.3 5 Whys

The 5 Why's is a systematic approach to get to the root cause of a problem. In this approach, questions are asked generally 5 times to get down the bottom of the problem in understanding the cause/effect relationships. It should be the practice of employees to ask questions in order to determine the ultimate root cause of a defect or problem. This is one of the most powerful and simple methods to access the tacit knowledge embodied in the employees' head, and to generate explicit knowledge in the documents and reports. Hence, it can be used to support knowledge creation in all SECI modes. A summary of the ten lean tools and methods, which support SECI modes, along with corresponding 'ba' and knowledge assets, is provided in Table 4.

CHAPTER 4. AN EXTENDED FUZZY-AHP APPROACH TO RANK THE INFLUENCES OF SECI MODES ON THE DEVELOPMENT PHASE

4.1 INTRODUCTION

Capturing, sorting, storing and retrieving information from a system are widely discussed topics in the product development (PD) projects. These systems essentially offer the advantages of dealing with the existing explicit knowledge. Naturally, increased internal efficiency can be associated with such initiatives. But, both academia and practitioners consider knowledge creation as a key source of growth and an imperative tool to maintain the sustainable competitive advantage (Madhavan and Grover, 2008). Traditional systems however, have a trivial impact on innovation owing to the absence of any process and/or tool for knowledge creation (Fahey and Prusak, 1998; Tyagi et al., 2015(b)). This is due to the fact that one can't solve new and unfamiliar problems and issues (arising from changes in the PD phases) with the existing old knowledge. An employee is required to possess knowledge creation ability in order to deal with them. Therefore, exploring methods intended to assist employees in performing tasks excellently by creating and enabling knowledge is a modern challenge faced by many organizations (Bratianu and Orzea, 2010). An important question that needs to be asked here is "*is there any theory which can be applied to knowledge creation.*" This question has apparently resulted in development and adoption of various models and best practices to represent the processes pertaining to knowledge creation. This chapter primarily targets the SECI model of knowledge creation presented by Nonaka (1994). In this model, the processes of interplay between tacit and explicit knowledge are categorized into four modes. These four modes referred with the acronym SECI are Socialization (tacit to tacit), Externalization (tacit to explicit), Combination (explicit to explicit), and Internalization (explicit to tacit). All SECI modes are conceptually linked and utilized within distinct PD phases with a view to improve the performance of the end product or service (Nonaka and Konno, 1998; Pitt and Clarke, 1999; Chatenier et al., 2009; Hammad and Nikolaos, 2013). This dissertation challenges this conventional assumption that all SECI modes affect a PD phase. If there is an effect, can all the four SECI modes be assumed to have a positive influence on improving the performance, is a question that still needs to be investigated. Extensive literature review clearly indicates that a very limited work has been done on this topic and therefore a research gap exists. This dissertation is an attempt to bridge the gap.

As mentioned earlier, the research in this chapter challenges the fundamental approach of '*correlating all SECI modes with each PD phase*' encountered in the literature. This is due to the fact that selection of appropriate SECI mode(s) can significantly affect the efficiency of the strategic planning and help in saving the business resources. In this context, the SECI modes are explained as a foundation of knowledge creation and subsequently the ranking of their influences on development phase is analyzed. In order to rank SECI modes, an extended Fuzzy Analytic Hierarchy Process (EFAHP) approach is proposed as a solution methodology. The EFAHP approach embeds the merits of fuzzy set theory into a widely used decision making tool (AHP). AHP develops a hierarchy system and takes experts opinions into account in scoring the alternatives. The hierarchical structure in AHP approach requires identifying critical criterion and sub-criterion. Identification of an appropriate set of vital criteria and sub-criteria to compare SECI modes is a cumbersome task. This dissertation utilizes the knowledge and information collected from subject matter experts (SMEs) and a rigorous review of available literature in the respective areas. This dissertation identifies top five criteria that play a key role in providing the insights, evaluating and then comparing SECI modes during the development phase. These criteria include final design, reusability, functionality, collaboration, and intelligence. The criteria are further decomposed into 19 sub-criteria for proper handling of the underlying problem. These criteria and sub-criteria can be selected based on preferences of organizations, thus making it an adaptive solution that fits their needs.

In EFAHP approach, evaluation employs the pairwise comparison of two triangular fuzzy numbers (TFNs) developed from the linguistic preferences of a decision-maker. In such evaluation, the height of ordinate estimated from the intersection point of two TFNs is utilized to calculate the degree of possibility of one criterion over another (Chang, 1996; Chan et al., 2006; Chen et al., 2006). If two TFNs are not intersecting i.e. when the pessimistic value of one is less than the optimistic value of other $(t_{11}-t_{23} \geq 0)$, the corresponding value of degree of possibility is assumed to be zero (Zhu et al., 1999). However, this situation (two triangles are not intersecting) simply represents the case of one criterion being stronger than other and should not receive a zero value. This dissertation proposes to map the triangle edges with a normal distribution about X-axis and extend them until they intersect. This allows developing a mathematical formulation to estimate the values of height of ordinate (degree of possibility) instead of zero. Thus, EFAHP provides an opportunity to efficiently rank the alternatives by acting as an expert evaluation system for decision-making.

4.2 LITERATURE REVIEW

Simply put, knowledge is what one already knows, and practice of making it instantaneously available in a usable format to create value is knowledge management. Knowledge management has been the core focus of research for long and the vast literature primarily targeted on how to locate, store, or share the knowledge for internal competitive advantage (Davenport and Prusak, 1998; Alavi and Leidner, 2001; Nevo and Chan, 2007; Baek et al., 2008). However, research papers drawing attention on opportunities and limitations of knowledge creation are comparatively very low. Knowledge creation is defined as the process of continuously updating or increasing the knowledge base of what one knows now than what one didn't know before and keeping it accessible, and usable. The basic difference between knowledge management and knowledge creation is that former helps in filling the gaps to complete raw data/information but later actually assists in the problem solving. Alavi and Leidner (2001) asked interesting questions related to conditions that facilitate knowledge creation in an organization, incentives that encourage knowledge contribution and support that triggers effective knowledge transfer. Goffin and Koners (2011) supported that interactions and actions among internal and external knowledge resources can be leveraged to create knowledge. With this regard, state-of-art SECI model is considered as most influential and is universally accepted. The details of the model are discussed in section 4.3.

Few works analyzed the SECI model in the PD environment from knowledge management perspectives. Pitt and Clark (1998), Chatenier et al. (1999), Krogh et al. (2000) and Hammad and Nikolaos (2013) conceptually linked innovation with dynamic knowledge, but they failed to provide detailed concepts and any empirical evidences. Existing empirical studies have targeted issues in domains other than development phase, such as knowledge creation during idea generation (Lee and Choi, 2003), solving technical problems (Corti and LoStorto, 2000), networking influences on knowledge creation (Hansen, 1999; Swan et al., 1999) etc. Madhavan and Grover (1998) and Schulze and Hoegl (2006) compared SECI modes within PD phases and advocated its importance in analysis of performance improvement. This research is built upon the work conducted by Schulze and Hoegl (2006) where they developed and tested the hypotheses to relate the product success with SECI modes performed during concept and development phases of the new PD projects. They found that PD success is positively influenced by socialization during the concept phase and combination during the development phase. Concept phase is adversely affected by externalization while development phase from socialization and internalization. However, their research did not incorporate any subjective criteria during analysis, hence constraining conclusions to a particular organization.

This dissertation proposes to use subjectivity and freedom in choosing criteria and sub-criteria for evaluation, making it a Multi-criteria Decision Making (MCDM) problem. Linear Programming best suits to reach the solution of a MCDM problem when decision needs to be made are under certainty. Most MCDM problems have a set of conflicting and uncertain objectives in the practical settings. Keeping this in mind, Thomas L. Saaty in 1980 introduced a simple yet systematic Analytic Hierarchy Process (AHP) method. Researchers and practitioners have widely exploited AHP to solve complex MCDM problem involving multiple and conflicting criteria. It is a useful, and practical method and has been used as a tool for weight estimation in deriving valid argumentative decisions for machine selection in flexible manufacturing system (Tabucanon et al., 1994), resource allocation by prioritizing information (Cheng and Li, 2001), supplier selection (Wang et al., 2004), reverse logistics and product recovery (Vadde et al., 2011), selection of innovative educational project (Melon et al., 2008) etc.

AHP is fundamentally built on two basic concepts: 1) formulation of the problem in a hierarchical structure, and 2) use of pairwise comparison. Hierarchical formulation breaks down the general or upper level uncertain or uncontrollable criteria into more particular or controllable ones. These criterions are subjected to a pairwise comparison to assign weights from a scale of 1 to 9. These absolute scale numbers (1-9) transforms the human preferences between available alternatives as equally, moderately, strongly, very strongly or extremely important to decide their resulting priorities. AHP is a better fit for prioritizing the alternatives based on numerical scales when ideas, feelings, and emotions play a role in decision-making process. So the central theme of AHP accounts for expert's opinion, subjective judgments, and preferences.

Despite obvious advantages of simplicity and easiness in use, AHP is not free from inherent pitfall as pointed out in recent publications (Dyer, 1990; Schenkerman, 1994; Lee et al., 2001; Chan et al., 2008). The traditional AHP demands judgments in crisp forms such as 1, or 3. Therefore, decision-making approximates vague human judgments in form of crisp values (Lee et al., 2001; Chan et al., 2008). The main shortcoming of AHP is related with the assumption of certainty in assessing the relative importance of criterions because real world decision problems are complex and vague. The decision-maker often feel uncomfortable and difficulty in assigning exact (crisp) numerical values for uncertain human preferences (Chan et al., 2008). The use of discrete scale cannot effectively handle the ambiguity in deciding these preferences. However, s(he) can provide comparisons in form of fuzzy judgments confidently. Hence, the need of adequately handling the inherent uncertainty and vagueness in mapping the individual's perception to exact numbers arises. In order to bridge this gap, the fuzzy set theory was introduced into AHP (Van laarhoven and Pedrycz 1983).

Fuzzy set theory, developed by Zadeh (1965), mathematically represents the human judgments to capture the impreciseness and vagueness of the approximate information. The fuzzy set theory resembles human reasoning in incorporating unquantifiable, uncertain information and partial facts into the decision model. It can effectively handle uncertainty by using interval or fuzzy evaluations matching with the variations in the decision-maker's input information (McCauley-Bell and Badiru 1996; Yucheng et al., 2011). A fuzzy set is characterized by a membership function (Eq. 1) to calculate the membership function value (λ).

$$\lambda\left(\alpha \mid \tilde{T}\right) = \begin{bmatrix} \dfrac{(\alpha - t_1)}{(t_2 - t_1)} & (t_1 \le \alpha \le t_2) \\ \dfrac{(t_3 - \alpha)}{(t_3 - t_2)} & (t_2 \le \alpha \le t_3) \end{bmatrix} \tag{1}$$

Where, t_1, t_2, and t_3 represent the smallest possible value (pessimistic), the most promising value and the largest possible value (optimistic) for a fuzzy set. These three point estimates are converted into triangular distribution for simplicity in calculation purposes. Collectively, these triplets (t_1, t_2, t_3) form a triangular fuzzy number (TFN) of a fuzzy set which is illustrated by putting '~' on letter T (called as *about T*). If $\tilde{T}_1 = (t_{11}, t_{12}, t_{13})$ and $\tilde{T}_2 = (t_{21}, t_{22}, t_{23})$ are two TFNs then the addition or subtraction, multiplication, division operations of two TFNs and inverse operation of a TFN discussed in Chang et al. (1996) hold true.

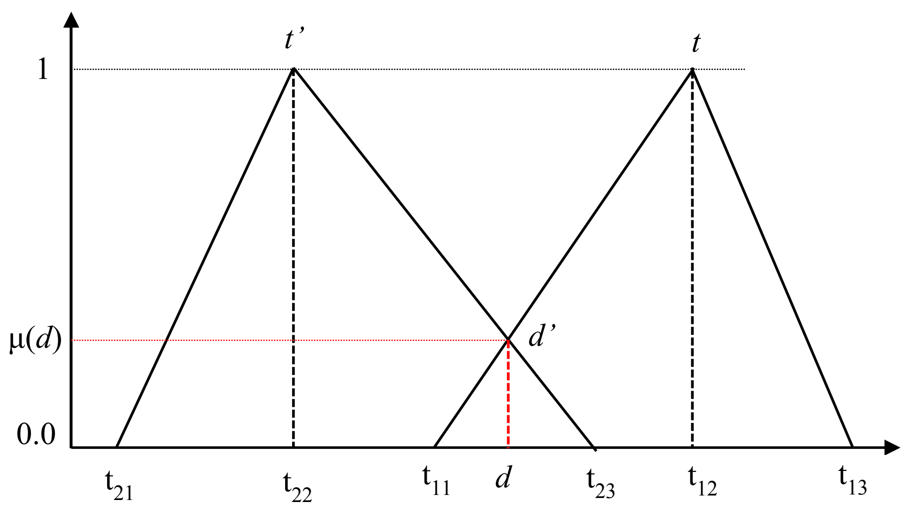

Figure 12: Illustration of two TFNs intersecting at a point *d*

Van-Laarhoven and Pedrycg (1983) utilized TFNs and obtained the priority vectors using logarithmic least squares method. Chang (1996) introduced a mathematical formulation for extent analysis approach to estimate the synthetic extent values of the pairwise comparisons and the degree of possibility when $(t_{11} - t_{23}) \le 0$ (See Figure 12). The mathematical formulation primarily takes into account the ordinate of highest intersection point of two TFNs (see Eq. 9).

However, if (t_{11}- t_{23}) ≥0 (when two TFNs don't intersect), the values are taken normalized (see Chang (1996) on page 653). Zhu et al. (1999) extended it and provided a proof that if (t_{11}- t_{23}) ≥0 (see Figure 17), then the value of degree of possibility should be zero. Further, Wang et al. (2008) criticized this 'zero' value approach since this method was found unable to derive the true weights (for fuzzy or crisp comparison). They also concluded that extent analysis method does not estimate the correct relative importance of decision criteria and hence of alternatives. The authors of this dissertation also agree with the conclusion of Wang et al. (2008). This is due to the fact that a zero value approach can result in zero priority weight to a criterion or an alternative in the extent analysis method. This assumption simply omits that particular criterion or alternative from further decision-making analysis. If that is the case, then the criterion or alternative should not be included while developing the comparison matrix in the start. During our analysis, it was found that these two TFNs do not intersect because one criterion or alternative is highly important than the other and should not receive a zero weight. An approach to estimate the true degree of possibility based on mapping of a TFN by a normal distribution with respect to X-axis until they intersect is introduced. Best to our knowledge from comprehensive literature review, this is the first attempt to propose such implementation of an extended Fuzzy-AHP. Therefore, this study provides a good breakthrough in decisions-making with greater precision.

4.3 PROBLEM FORMULATION

Organizations are thriving to sustain in existing competitive markets and aspiring to enter as well as create new markets. This is simply possible by developing and offering the high quality products at lowest cost. The vital ingredient for creative PD is employee's knowledge base that actually determines and adds value. Additionally, such decisive knowledge is of paramount importance in shortening the development cycle and reducing the stupendous expenditure of unplanned risks. This puts pressure on organizations to effectively create, update, and handle knowledge. In this context, the effect of SECI modes on development phase from knowledge creation and transfer perspectives are investigated in this dissertation. This helps a team to make informed-strategic decisions to improve their performance.

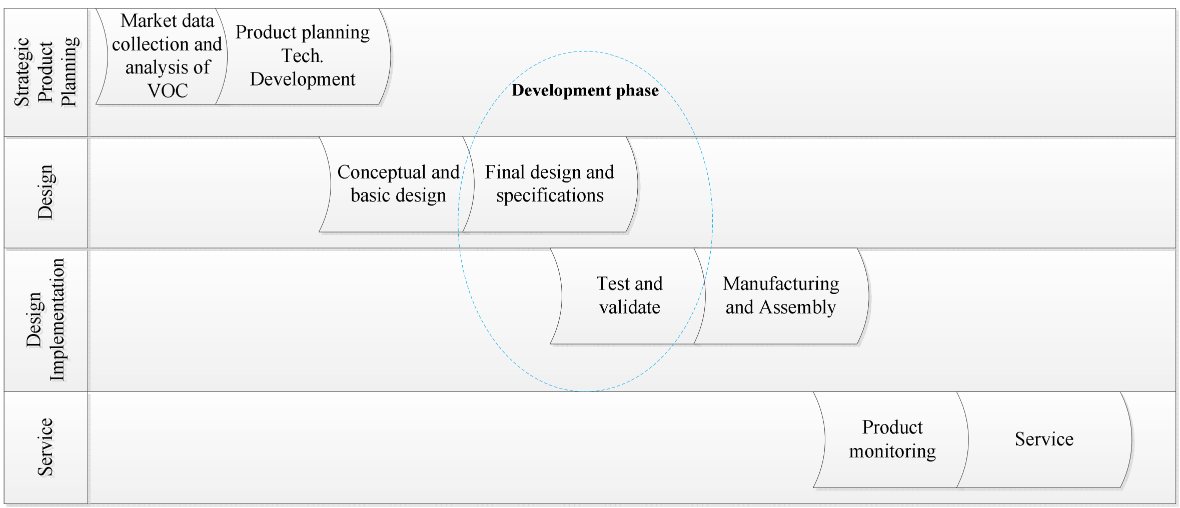

Figure 13: The PD process and high level steps considered under development phase

4.3.1 Development phase

Investment in quality improvement efforts at development phase is ten times more effective than during production phase (Morgan and Liker, 2006). This phase lies between concept phase and manufacturing phase (see Figure 13). During development phase, the customer requirements are transformed into concrete deliverables in form of product designs and their application in real settings are validated. The successful completion of this important phase requires a complete set of design specifications and proper description of processes, standards, and tools (Cai et al., 2011; Cai et al., 2014). The emphasis is also given on meeting quality, time, and schedule objectives and formal project planning ensures that project progresses accordingly. The details of identified criteria and sub-criteria are discussed next.

4.3.2 Important criteria/sub-criteria during development phase

Intensive review of available research and a prolonged discussion with SMEs from strategic decision areas are conducted before picking the top five criterions. These criteria are further divided into nineteen important sub-criteria. The applicability of each sub-criterion for development phase is detailed next.

- Final design

The product and process designs directly affect the performance of the development phase. This is due to the fact that collectively they determine a major portion (around 80%) of the manufacturing costs (Rapp, 2000). Before confirming their design, all the planned approaches and activities for the integration of hardware, software, and other components are tested. Design rules, and technologies are specified and/or acquired and final details of the product/process architecture are established and documented while performing the necessary research work. This helps in defining the arrangement of a functional system with sub-systems and their behavior as a unit. Processes capturing already known and acquired new knowledge on a daily basis are also mandatory. All current product variant(s) is another criterion that affects the performance of development phase. The relative position of the final product specifications with respect to competitor's and own product's portfolio should be assessed by gathering pertinent information. Having a product with meaningful characteristics better than the competitors increases the likelihood of the commercial success.

- Product design (DD)

Development phase ensures that established final product design meets all the business needs and has been benchmarked with other designs. Furthermore, general product characteristics such as part material, product configuration, surface finish, and tolerances are also finalized. The bottom line is that after successful development phase, the final design must reflect the customer needs, differentiate the product from the competition, and demonstrate technical and economic feasibility of a ready to launch product (Darlington and Culley, 2004).

- Process design (SD)

After prioritizing product designs, the general characteristics affecting process design such as part handling, tooling type, and operations sequencing must be determined. Process design is a critical phase that typically occurs concurrently with the product design (Tyagi et al., 2012). It focuses on increasing efficiency and productivity by eliminating risk of losing value through inefficient or inappropriate operation activities. The process design should be optimized to support and sustain organizational growth. It may need a tweak into existing processes for some quick wins (modest changes) or radical changes to accommodate aggressive alterations for major opportunities. Documented business processes reduce the learning curve duration and sets clear expectations.

- Product portfolio (PF)

The product portfolio basically encompasses all the variant(s) of a product that an organization is developing and producing. An engineer working on more than one product can create knowledge and apply that knowledge for improving the performance of development phase. For example, tacit knowledge gained during activities of one product can bring different perspectives to take well-informed decisions (McNally et al., 2013). The overall goal is to implement accumulated organizational knowledge, technical knowledge, and/or a combination of both from one product variant to other during development phase.

4.3.2.2 Reusability

Reusability is required for efficient handling of the development phase. The development team should write comprehensive, and easy to understand documents with no redundant information for other teams and future reuse. Such collected information from documents of past projects should be recycled and integrated with current projects where it’s possible and beneficial. This is intended to save time and business efforts for current projects (Chan et al., 1986).

- Project briefings (PB)

In project briefings, present project team learns from seasoned employees of the past projects typically in a workshop. The seasoned employees share important issues faced by them in a structured way with examples and illustrations. This is primarily done to share relevant technical issues or problems and other objectives such as cost, time and quality (Hoegl and Schulze, 2005).

- Lessons learned (LL)

The critical project information and other deliverables, irrespective of positive or negative experiences, from all life-cycle phases should be organized and documented in a repository for easy access, store, and reference. These documents should also include information related to any preparation before development or modification of a product and other item (Hoegl and Schulze, 2005). The objective is to capture the valuable knowledge revealed during the past projects and their learning by the team members. The documentation of lessons learned for future projects should be supported and use of these lessons learned from past projects should be promoted.

- Best practices (BP)

The best practices are characterized by the description of effective processes in successfully completing the same task multiple times. Before selecting any practice as best practice, several common and good practices should be compared. The description of best practices should have a problem statement, relevant circumstances, solution steps, and required information specifications to conduct the tasks (Cooper et al., 2005). They are dependent on context hence does not claim universal applicability. The best practices should be understood in details and modified before considering them into other perspectives. Documentation and necessary modification of best practices should be supported for wider applicability.

- Databases (DB)

Extensive calculations and simulations are performed for testing. The outcomes of testing should be systematically recorded to assist the future developments. A disciplined approach to analyze data reduces time in data management, improves quality and consistency of information, and turns disparate information into a valuable resource. These databases must be kept current, and coded for seamless and intuitive accessibility (Tham et al., 2006). The database offers knowledge to make the right and accurate decisions.

4.3.2.3 Functionality

As mentioned earlier, part functions/properties and their interaction must be identified, correlated and analyzed with product requirements and properties. As a result, the user may need to flow down the specifications and further refine them as appropriate, reflect them on the product/process and make trade-offs where necessary. Additionally, the technical and cost models of the product must be developed while establishing the final specifications (Cai et al., 2014). With their help product concepts are exercised before selecting the final design. For continuous innovation, functionality is vital in identifying required properties and transforming them into actions.

- Simulations (SM)

An engineer performs integrated calculations of stress, deflection, and motion to validate designs in a simulation by evaluating how moving parts interact and design functions under real settings. Engineers create documentations which are required by the production team to perform accurate analysis and evaluation. Effective use of simulation ensures best possible design decisions to sharply reduce uncertainty and risks. A simulation also testes and validates prototypes to enhance the confidence regarding absence of serious problems in future (Tyagi et al., 2007). Moreover, digital prototypes can be tested immediately under realistic conditions. The digital prototyping speeds up the development cycles by eliminating the need of a physical prototype.

- Review meetings (VM)

Review meetings are convened to present designs and to gain multi-disciplinary opinions. In these meeting, designs are appreciated, critiqued, peer reviewed to investigate its existing capabilities and deficiencies (Farris et al., 2011). Further action plans are developed and formulated to implement routine deliverable reviews to correct inaccuracy, incompleteness, and ambiguities (Meekings, 2005). These meetings also provide means for assessing progression to the next stage of development or testing.

- Change management (CM)

Complex PD process and upfront lack of knowledge forces users to avoid or bypass changes only to find out at the later stages. A high number of cross-functional teams further complicate the situation. Loss of the valuable design and configuration results in incomplete or incorrect knowledge/documentation causing severe problems for downstream stages (Lin et al., 2014). This is owing to the fact that making changes in the front end of the design process is easier but as product matures, the change complexity and cost of change increases exponentially (see Figure 14). Change management deals how these changes are planned, communicated, analyzed, implemented, and released as the product evolves. Documenting changes and reasons that caused them and their solution for future reuse is required for efficient change coordination and information utilization.

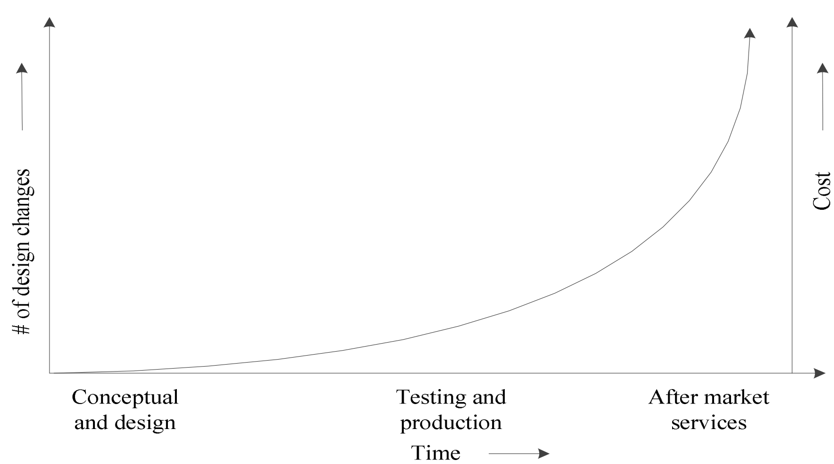

Figure 14: The change in cost between front end vs back end

- Risk mitigation (RM)

Activities of identifying, analyzing and managing the risks are conducted to stop a product from failures in the future. In the identification, initial risks affecting the product and their characteristics are determined. Next, each identified risk is analyzed using quantitative and/or qualitative analysis. The details of risk analysis method and conditions are also described.

Furthermore, response plans and strategies are developed to mitigate, transfer or avoid them. In the end, procedures to monitor and control the identified and new risks are defined (Smith 1999). Risk mitigation requires identifying them within whole life-cycle and knowledge to analyze and align them with other departments for efficient management.

4.3.2.4 Collaboration

Collaboration supports and enables the process of human interactions for decision-making in the organizational context. Knowledge artifacts serve as a medium of interaction between a team of co-workers and/or among stakeholders. Procurement of appropriate systems and services through collaborative efforts demonstrates a clear value for business case. The pre-requisite factors for an efficient collaboration are professional relationship with partners, structured organization and work processes, recognition and reward systems, superior leadership models and practices, and team competencies. Collaboration is a norm in companies and cultures for successful and innovative future.

- Compatible (CO)

A newer version of a product is considered compatible when design and/or data of an older version of the same product build it. The importance is vindicated by the fact that it eliminates the need to start over when older version is upgraded (which is true in most cases in present scenarios). This generally forces an organization to keep products compatible across multiple-generations. However, it is also necessary to sacrifice compatibility to exploit modern technologies.

- Relationship with partners (RP)

The decision of producing the components in-house or purchasing must be determined and the suppliers should be identified upfront. Suppliers and customers share ideas, provide and receive critical feedback and hence a tremendous amount of knowledge is exchanged. As acquisition of tacit knowledge is important for new product success, the relationship strength greatly influences the end product performance (Maffinn and Braiden, 2001). Acquiring such knowledge from partners is necessary in today's complex and uncertain environment (Chan et al., 2008). Partner's understanding of a firm's vision to develop a long-term partnership is also required.

- Common understanding (CU)

Ensuring that there is a common understanding regarding product, process design etc. among team members and stakeholders is imperative. Common understanding supports smooth sharing of experiences, and values to enhance mental models and technical skills in the uncertain and rapidly changing business environments. Records can be used to emphasize the opportunities of adapting and integrating them with decisions of other projects on an ongoing basis. This helps in nurturing the common understanding among employees and integrating the knowledge from other projects.

- Competence (CT)

Employees are the most important assets of an organization and core competencies they possess are needed to face current and future challenges. Critical thinking, communication, and stewardship are among the top competencies required (Gabčanová, 2011). These core competencies aid in identifying and evaluating the right opportunities important for growth of an organization.

4.3.2.5 Intelligence

A new employee has a relatively steep learning curve owing to possibly different working culture, terminologies, product, and processes. They rarely receive any manual to demonstrate how work is done internally. And if they receive something, those manuals generally are either very comprehensive or very scarce (Schneider and Bowen, 1993). A precise yet dynamic tool that can offer a new employee a work form, and contribute in augmenting individual's abilities and expertise is important. In this way, the team members throughout the company can easily learn and quickly bridge the learning cycle gap and mental models. Learning of new things mainly takes place through individuals and their communication efforts.

- Informal events (IE)

Open communication and discussion during informal events encourage transfer of tacit knowledge among team members. The entire company workforce from all locations should come together after a constant period for this purpose. It is worthwhile to build the personal networks and knowledge exchange even at a significant cost (Hoegl and Schulze, 2005). This exercise results in nurturing confidence among teams to arrive at new insights and more accurate interpretations as opposed to individuals. Team builds better solutions that help in resolving issues quickly and increase job satisfaction for team members. Therefore, the performance of a project is likely to improve (Alavi and Leidner, 2001).

- Comprehension (CH)

Comprehension encompasses the process of gaining intelligence from interaction with the external environment. The resulting intelligence is combined with other projects regularly in order to identify problems, and opportunities. It follows "learning by doing" or re-experiencing philosophy to transform the explicit knowledge into tacit knowledge (Oinas-Kukkonen, 2005).

The comprehension by incorporating the documented approaches into mental models should be supported.

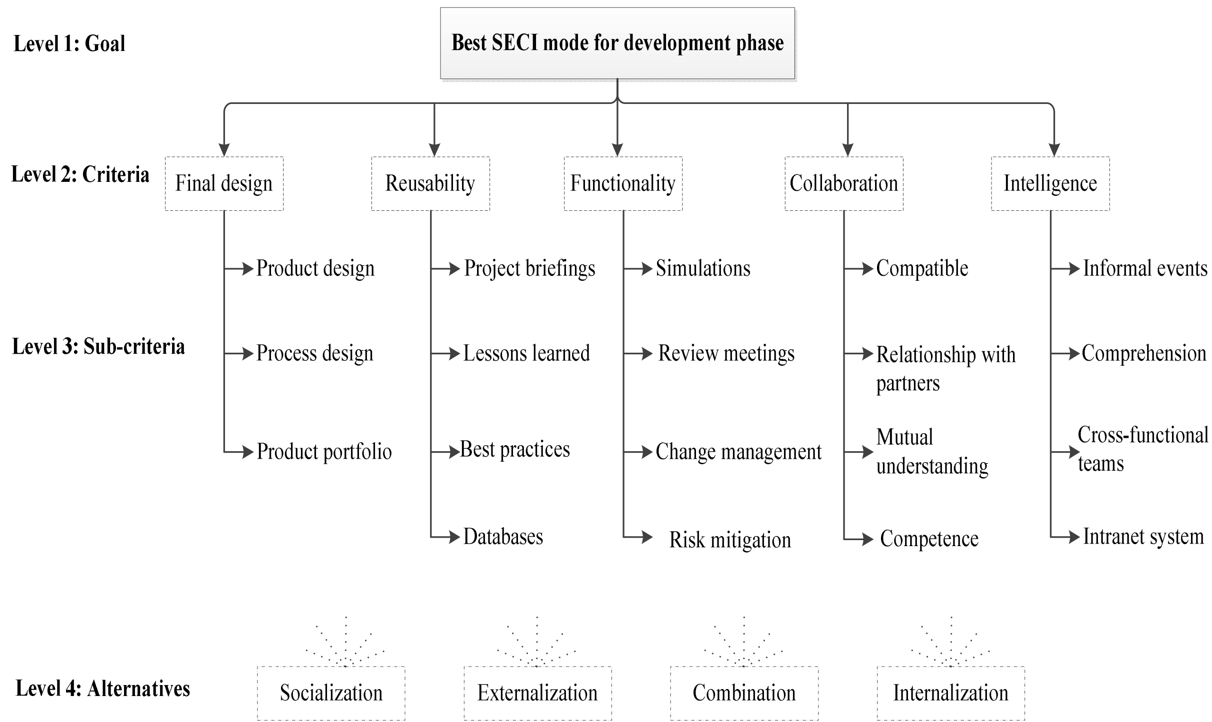

Figure 15: Hierarchical structure of ranking the SECI modes for development phase

- Cross-functional teams (CF)

A group of people working together who collectively represent the interests of an organization is called a cross-functional team. Strong and healthy cross-functional teams are imperative for broad communication, easy alignment of goals and improved products to dominate the market against competition (Sethi et al., 2001). The successful cross-functional team enhances creativity and innovation, quickens problem solving, and escalates learning (Parker, 2001). While working as a team, individual easily get and access updated information and brings up encountering issues or roadblocks to enhance useful capabilities in broader way and update documents.

- Intranet system (IS)

The intranet system primarily contains knowledge elicitation, access to expert problem solvers, and reporting. The vast knowledge in intranet system acts as a learning guide or an online coach for users to solve problems by following a rigorous reasoning process (Wilde and Murray, 2009). Intranet system is advocated to define new problems and countermeasures or append them with the existing ones. The process progresses in stages to lead towards either an already explored permanent countermeasure or an unidentified/unsolved problem. The temporary fixes of the closed problems are documented in intranet system and others (unsolved problems) are either removed or integrated into the permanent countermeasures. In order to solve problems, questions are formatted in a specific sequence to elicit user's reasoning. Individuals typically form reasoning based on tacit knowledge. This reasoning from gained experience reflects their perspectives on the situation's unique context (Edenius and Borgerson, 2003). Furthermore, written down documents allow others to access the wealth of tacit knowledge applied into problem solving. The hierarchical structure of the underlying problem is summarized in Figure 15. The next section presents the details of AHP, Fuzzy set theory, and EFAHP implementation for underlying problem.

4.4 PROPOSED METHODOLOGY – THE EFAHP APPROACH

The EFAHP approach is highly relevant to solve the problem at hand considering multi-criteria structure and vagueness in real environment. This systematic approach basically integrates two fundamentally distinct concepts, the fuzzy set theory and the AHP. The advantage of fuzzy set theory is in dealing with the ambiguity intrinsic to the decision-making problems and the ability to define vague data using classes and grouping with boundaries (Nguyen, and L., Gordon-Brown, 2012; Yuen, 2014; Xu and Liao, 2014). This fuzzy extension is required because the basic AHP model misses the important aspect of tackling the high degree in vagueness of personal subjective judgments and individual preferences. The EFAHP approach represents the linguistic variables of human feelings and judgments by a TFN for conducting the pairwise comparisons. The pairwise comparison utilizes a membership function (Eq. 1) to determine the relative importance. The implementation steps of the EFAHP method are detailed next.

Step1: Develop fuzzy comparison metrics

The decision-maker is asked to facilitate the comparison of one criterion over another in linguistics terms while keeping the overall goal in mind. Here a simple question is asked: according to him/her "how important is one criterion (for example criterion μ_1) over another (μ_2) in terms of primary goal." The user can simply put them as criterion μ_1 is fairly important as compared to criterion μ_2. The linguistic terms corresponding to Saaty's scale (Saaty, 1980), their definition and TFN are shown in Figure 16. According to this table, TFN value for this comparison is (4, 5, 6). However, when criterion μ_2 is compared against μ_1 TFN changes to (1/6, 1/5, 1/4). The comparisons in linguistic terms for the numerical analysis are shown in Table 5 in Section 6.

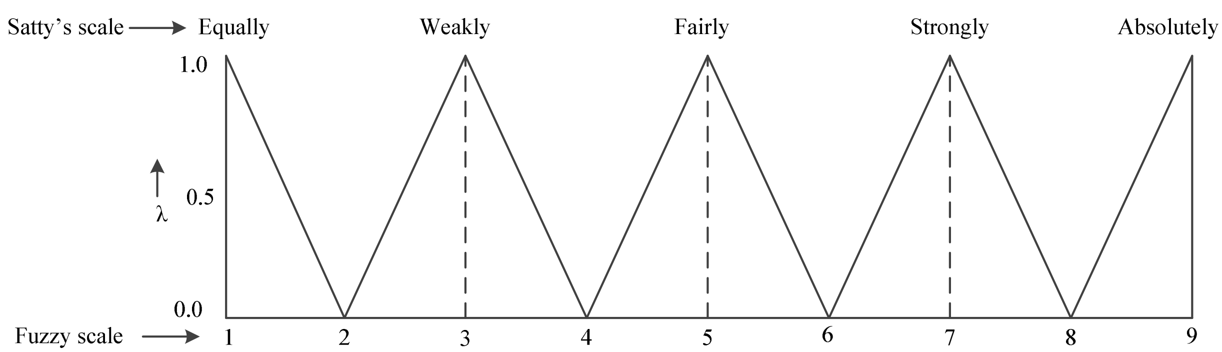

Figure 16: Fuzzy definition and TFN corresponding to Saaty's scale

Step 2: Calculate fuzzy synthetic extent value (E_c)

E_c for c^{th} criterion with respect to any object (o) is estimated by Eq. (2)

$$E_c = \sum_{a=1}^{p} T_{oc}^{a} \otimes \left[\sum_{b=1}^{q} \sum_{a=1}^{p} T_{oc}^{a} \right]^{-1} \quad (2)$$

Where, T_c^a (a = 1, 2 …, *p*) denotes a TFN and object *o*=(1, 2, 3). The value of $\sum_{a=1}^{p} T_c^a$ is estimated by adding the fuzzy values for *p* extent analysis using addition operation.

$$\sum_{a=1}^{p} T_c^a = \left(\sum_{a=1}^{p} t_{a1}, \sum_{a=1}^{p} t_{a2}, \sum_{a=1}^{p} t_{a3} \right) \quad (3)$$

$$\sum_{b=1}^{q} \sum_{a=1}^{p} T_c^a = \left(\sum_{b=1}^{q} t_{b1}, \sum_{b=1}^{q} t_{b2}, \sum_{b=1}^{q} t_{b3} \right) \quad (4)$$

$$\left[\sum_{b=1}^{q} \sum_{a=1}^{p} T_c^a \right]^{-1} = \frac{1}{\sum_{b=1}^{q} t_{b3}}, \frac{1}{\sum_{b=1}^{q} t_{b2}}, \frac{1}{\sum_{b=1}^{p} t_{b1}} \quad (5)$$

Step 3: Determine the comparative superiority

The comparative superiority of one TFN $(\tilde{T}_1 = t_{11}, t_{12}, t_{13})$ over another TFN $(\tilde{T}_2 = t_{21}, t_{22}, t_{23})$ is defined as $S(\tilde{T}_1 \geq \tilde{T}_2) = min\left(\lambda\left(x \mid \tilde{T}_1\right), \lambda\left(y \mid \tilde{T}_2\right)\right)$

Where, a combination of (*x, y*) is such that they follow $x \geq y$ and for some combination of *x* and *y* there exists $\lambda\left(x|\tilde{T}_1\right) = \lambda\left(y|\tilde{T}_2\right) = 1$. From here on, the tilde is removed from T_1 and T_2, just to simplify the representation and analysis. Since T_1 and T_2 are convex fuzzy numbers (Chang, 1996), therefore,

$$S(T_1 \geq T_2) = 1 \text{ iff } t_{11} \geq t_{21} \quad (6)$$

$$\text{for the same combination of } t_{11} \geq t_{21} \; S(T_2 \geq T_1) = hgt(T_2 \cap T_1) = \lambda\left(d \mid T_1\right) \quad (7)$$

Where, *d* is the point of highest interaction between two TFNs as shown in Figure 12. The ordinate for such two triangles $(T_1 = t_{11}, t_{12}, t_{13})$ and $(T_2 = t_{21}, t_{22}, t_{23})$ is estimated using Eq. 7 if $t_{21} \geq t_{11}$ and $t_{11} - t_{23} \leq 0$.

$$\text{hgt}(T_2 \cap T_1) = \frac{(t_{11} - t_{23})}{(t_{22} - t_{23}) - (t_{12} - t_{11})} \qquad (8)$$

The values of for both S($T_1 \geq T_2$) and S($T_2 \geq T_1$) must be calculated in order compare T_1 and T_2. Eq. 6 and Eq. 8 are summarized in Eq. 9.

$$S(T_2 \geq T_1) = \begin{pmatrix} \dfrac{(t_{11} - t_{23})}{(t_{22} - t_{23}) - (t_{12} - t_{11})} & t_{11} \geq t_{21} \; \& \; t_{11} - t_{23} \leq 0 \\ 0 & \text{Otherwise} \end{pmatrix} \qquad (9)$$

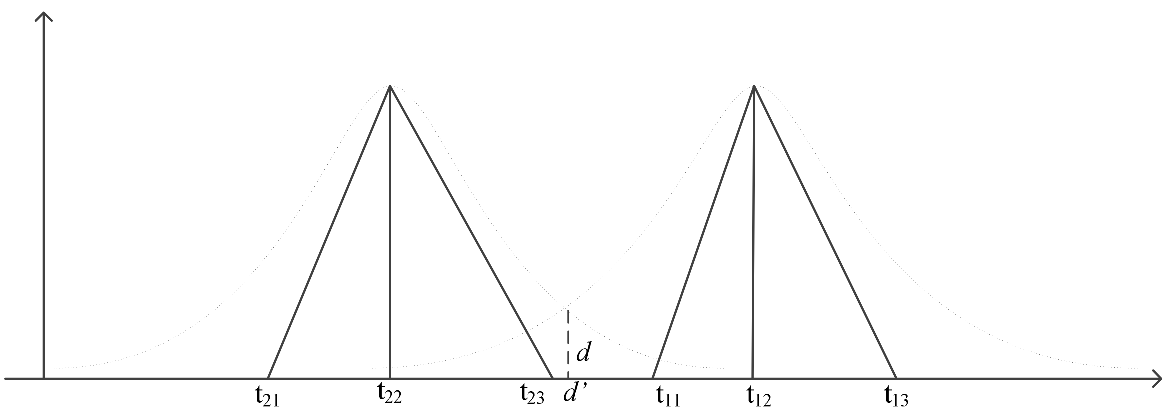

Figure 17: Extension of two triangles to normal distributions

The resulting value of Eq. 9 is employed to estimate the comparative superiority of one TFN over another when they intersect. The situation where two TFNs don't intersect (t_{11}-t_{23}≥0) is illustrated in Figure 17. In this figure, two TFNs are mapped with normal distributions extended with respect to X-axis so that they cut at point d' as represented by the dotted lines. These extended edges of normal distributions are considered to compute the comparative superiority of two criterions (Buranathiti et al., 2004). A method to calculate the value of degree of possibility for two TFNs not intersecting with each other is proposed. The three-point estimates are used to calculate the approximate values of mean (μ) and standard deviation (σ) of a normal distribution. The most likely value (t_{12}) provides the mean value of a normal distribution and its standard deviation can be estimated using Eq. (10).

$$\text{The standard deviation } (\sigma) = \sqrt{\frac{(t_{23} - t_{11})^2}{36}} \tag{10}$$

For the analysis purpose, first the parameters of normal distribution from three-points are estimated. Then, the two normal distributions are drawn on MATLAB to find out the point of intersection on X-axis and height of intersection (h_{nd}). This height provides the true degree of superiority of one sub-criterion over another when triangles are not intersecting (see Figure 18). Therefore, the Eq (9) is updated to Eq. (11).

$$S(T_2 \geq T_1) = \begin{pmatrix} \dfrac{(t_{11} - t_{23})}{(t_{22} - t_{23}) - (t_{12} - t_{11})} & t_{21} \geq t_{11} \;\&\; t_{11} - t_{23} \leq 0 \\ h_{nd} & \text{Otherwise} \end{pmatrix} \tag{11}$$

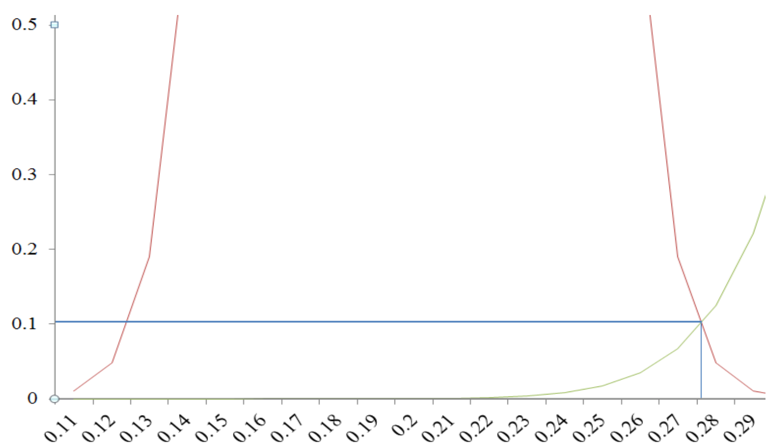

Figure 18: The intersection point of two normal distributions

Step 4: Select the minimum value of superiority

$$S(T \geq T_1, T_2, \ldots, T_l) = S\{(T \geq T_1) \text{ and } (T \geq T_2) \text{ and } \ldots \text{ and } (T \geq T_l)\} \tag{12}$$

$$= \min S\{(T \geq T_i)\} \quad \text{where, } i = 1, 2, \ldots, l \tag{13}$$

Step 5: Calculate weight vector and normalize it for each criterion

$$m(\pi_l) = \min S(E_i \geq E_l) \text{ for } \forall\, i = 1, 2, \ldots, l\,;\ except\ i = l \tag{14}$$

Then, the weight vector is estimated as

$$Wp=\{ m(\pi_1), m(\pi_2), \ldots, m(\pi_i)\}^T \quad (15)$$

This weight is normalized, and the normalized weight vector is expressed using Eq. (16).

$$W=\{ w(\pi_1), w(\pi_2), \ldots, w(\pi_i)\}^T \quad (16)$$

Step 6: Repeat step 1 to 5 to determine the normalized weight vector of the sub-criteria in response to the criteria. Furthermore, estimate the normalized weight of the alternatives corresponding to each sub-criterion.

Step 7: Multiply the normalized weight vector values of alternatives with that of sub-criteria and add them in order to estimate the partial priority weight value of an alternative.

Step 8: Multiply the normalized values of the criteria with the multiplication values of alternative and sub-criteria estimated in Step 7 and add them to estimate the final priority weight. Mode with highest final priority weight value has the most influence on the development phase.

4.5 NUMERICAL EXAMPLE AND ANALYSIS

The PD process follows a sequence of activities, deliverables, methods and tools to design and develop high quality products that exceed customer expectations (Tyagi et al., 2015(a)). The development phase predominately has activities pertaining to developing a mature concept design. The engineering work remained is to complete and test the detailed parts and modules. The major deliverables include established engineering drawing, documented product information, applying quality analysis tools such as QFD, conducting Design Failure Modes and Effects analysis, design reviews, testing parts and establishing the bill of material (see Figure19). Therefore, designers are no longer merely exchanging geometric data, but more general knowledge about design and design process, including specifications, design rules, constraints, rationale etc. are shared (Cai et al., 2014). During execution of these tasks, fresh requirements are targeted to achieve. For this, existing knowledge from past projects is not sufficient, resulting in new obstacles in form of the unfamiliar and unsolved problems. In order to solve them, engineers wonder around and struggle in selecting the right tool to reach the solution. Ultimately the problems are solved in practical settings but in this competitive environment, time is the decisive factor. Knowledge creation ability to quickly resolve an unfamiliar issue is critical. A list of established customized tools to choose from for a specific phase to support knowledge creation and transfer can become handy in minimizing the business efforts. Therefore, organizations are interested in comprehensibly evaluating the SECI modes for proper utilization of resources in order to achieve critical but relatively important goals.

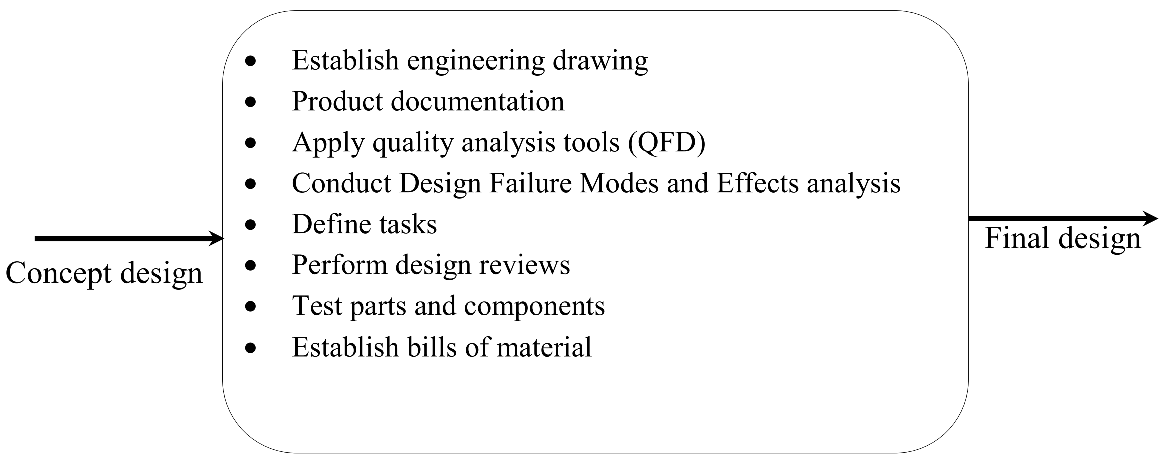

Figure19: Input, output, and tasks of the development phase

This chapter attempts to present a mathematical model to solve this problem in a realistic environment. For this, first the overall goal and what an organization is trying to accomplish are finalized. Next criteria and sub-criteria critical in achieving the overall goal are identified (see section 3). Handling more than 7–9 factors simultaneously is cumbersome in accurate decision-making. Considering this, the complex problem (selecting the best mode that positively affects the development phase) is broken down into four hierarchical levels for ease in managing the analysis. The first level in hierarchy is goal which is to select the best SECI mode(s) for development phase. Next in hierarchy are criteria at second level, followed by sub-criteria at third level, respectively. The alternatives (SECI modes) are placed at the bottom or fourth level of hierarchy (see Figure 15). Once the hierarchy was formed, the EFAHP approach is exploited to estimate the priority weights of criteria, sub-criteria and alternatives. SME's opinions are incorporated in order to decide the preferences of one criterion over another. The method for calculating the priority weights with respect to overall goal is demonstrated in this section.

Step1: The pairwise comparison of different criterion against the overall goal is conducted to construct the fuzzy comparison matrix (Table 5) and then priority value of each criterion with respect to the overall goal is calculated (Table 6).

Table 5: Pairwise comparison to determine metrics with respect to the overall goal

A	*S*	*F*	*W*	*Criterion*	*E*	*Criterion*	*W*	*F*	*S*	*A*
(9,9,9)	*(6,7,8)*	*(4,5,6)*	*(2,3,4)*		*(1,1,1)*		*(2,3,4)*	*(4,5,6)*	*(6,7,8)*	*(9,9,9)*
	X			Reusability		Final design				
		X		Functionality		Final design				
				Collaboration		Final design		X		
	X			Intelligence		Final design				
				Functionality		Reusability		X		
				Collaboration		Reusability		X		
				Intelligence		Reusability			X	
			X	Collaboration		Functionality				
				Intelligence		Functionality		X		
				Intelligence		Collaboration	X			

Table 6: Metric values for criteria with respect to overall goal

Criterion	*Final Design*	*Reusability*	*Functionality*	*Collaboration*	*Intelligence*	*Weight*
Final Design	(1,1,1)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(4,5,6)	(1/8,1/7,1/6)	0.08
Reusability	(6,7,8)	(1,1,1)	(4,5,6)	(4,5,6)	(6,7,8)	0.43
Functionality	(4,5,6)	(1/6,1/5,1/4)	(1,1,1)	(1/4,1/3,1/2)	(4,5,6)	0.04
Collaboration	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(2,3,4)	(1,1,1)	(2,3,4)	0.20
Intelligence	(6,7,8)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	0.25

Step 2: Eq. (5) is employed to estimate E_1, E_2, E_3, E_4 and E_5 for each criterion.

$$E_1 = (5.42, 6.49, 7.58) \otimes (48.71, 59.10, 69.75)^{-1} = (0.08, 0.11, 0.16)$$

$$E_2 = (21.0, 25.0, 29.0) \otimes (48.71, 59.10, 69.75)^{-1} = (0.30, 0.42, 0.59)$$

$$E_3 = (9.42, 11.53, 13.75) \otimes (48.71, 59.10, 69.75)^{-1} = (0.14, 0.20, 0.28)$$

$$E_4 = (5.33, 7.40, 9.50) \otimes (48.71, 59.10, 69.75)^{-1} = (0.08, 0.13, 0.19)$$

$$E_5 = (7.54, 8.68, 9.92) \otimes (48.71, 59.10, 69.75)^{-1} = (0.11, 0.15, 0.20)$$

Step 3: Eq. (11) are used to calculate the comparative superiority value of E_i over E_j ($i \neq j$).

$S(E_1 \geq E_2) = 0.22$ (calculated using intersection of two normal distribution);

$$S(E_1 \geq E_3) = \frac{(0.135 - 0.156)}{(0.11 - 0.156) - (0.195 - 0.135)} = 0.19$$

$$S(E_1 \geq E_4) = \frac{(0.076 - 0.156)}{(0.11 - 0.156) - (0.125 - 0.076)} = 0.84$$

$$S(E_1 \geq E_5) = \frac{(0.108 - 0.156)}{(0.11 - 0.156) - (0.147 - 0.108)} = 0.56$$

$S(E_2 \geq E_1) = 1$ $S(E_2 \geq E_3) = 1$ $S(E_2 \geq E_4) = 1$ $S(E_2 \geq E_5) = 1$

$S(E_3 \geq E_1) = 1$ $S(E_3 \geq E_2) = 0.09$ $S(E_3 \geq E_4) = 1$ $S(E_3 \geq E_5) = 1$

$S(E_4 \geq E_1) = 1$ $S(E_4 \geq E_2) = 0.55$ $S(E_4 \geq E_3) = 0.46$ $S(E_4 \geq E_5) = 0.80$

$S(E_5 \geq E_1) = 1$ $S(E_5 \geq E_2) = 0.55$ $S(E_5 \geq E_3) = 0.59$ $S(E_5 \geq E_4) = 1$

Step 4: Using Eq. (18), minimum degree of superiority for each criterion is obtained.

$min\ (\pi_1) = min\ S(E_1 \geq E_2, E_3, E_4, E_5) = min\ (0.87, 0.19, 0.84, 0.56) = 0.19$

Similarly, $min\ (\pi_2) = 1.00$, $min\ (\pi_3) = 0.09$, $min\ (\pi_4) = 0.46$, $min\ (\pi_5) = 0.55$

Step 5: The weight vector with respect to criterion is estimated as

$Wp = (0.19, 1.00, 0.09, 0.46, 0.55)^T$

The normalized weight vector (W) is = $(0.09, 0.43, 0.04, 0.20, 0.24)^T$

Step 6: Steps 1-5 are repeated to determine the normalized weights of sub-criteria in response to criteria and that of alternatives with respect to sub-criteria (See Tables 7-11).

Criterion against the sub-criterion

Table 7: Metric values with respect to final design

	DD	*SD*	*PF*	*Weight*
DD	(1, 1, 1)	(4, 5, 6)	(6, 7, 8)	0.39
SD	(1/6, 1/5, 1/4)	(1, 1, 1)	(4, 5, 6)	0.07
PF	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	(1, 1, 1)	0.54

Table 8: Metric values with respect to reusability

	PB	*BP*	*LL*	*DB*	*Weight*
PB	(1, 1, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2)	0.05
BP	(2, 3, 4)	(1, 1, 1)	(4, 5, 6)	(2, 3, 4)	0.56
LL	(1, 1, 1)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/4, 1/3, 1/2)	0.10
DB	(2, 3, 4)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1, 1, 1)	0.28

Table 9: Metric values with respect to functionality

	SM	*RM*	*CM*	*VM*	*Weight*
SM	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(2, 3, 4)	0.31
RM	(4, 5, 6)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	0.31
CM	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	0.19
VM	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	0.19

Table 10: Metric values with respect to collaboration

	CO	*RP*	*CU*	*CT*	*Weight*
CO	(1, 1, 1)	(4, 5, 6)	(4, 5, 6)	(9, 9, 9)	0.18
RP	(1/6, 1/5, 1/4)	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	0.28
CU	(1/6, 1/5, 1/4)	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	0.38
CT	(1/9, 1/9, 1/9)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1, 1, 1)	0.16

Table 11: Metric values with respect to intelligence

	IE	*CF*	*PS*	*IS*	*Weight*
IE	(1, 1, 1)	(1/9, 1/9, 1/9)	(1/6, 1/5, 1/4)	(1/9, 1/9, 1/9)	0.52
CF	(9, 9, 9)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)	0.29
PS	(4, 5, 6)	(1/6, 1/5, 1/4)	(1, 1, 1)	(2, 3, 4)	0.08
IS	(9, 9, 9)	(1,1,1)	(1/4, 1/3, 1/2)	(1, 1, 1)	0.11

Step 7: Partial priority weight for combination mode is estimated as (see Tables 12-30):

{(0.39*0.58+0.07*0.26+0.54*0.32), (0.05*0.55+0.56*0.55+0.10*0.56+0.28*0.49), (0.31*0.59

+0.31*0.41+0.19*0.45+0.19*0.41), (0.18*0.49+0.28*0.35+0.38*0.50+0.16*0.43),

(0.52*0.47+0.29*0.40+0.08*0.59+0.11*0.50)} = (0.42, 0.53, 0.47, 0.45, 0.46)

Sub-criterion against the alternatives

Table 12: Metric values with respect to DD

DD	*S*	*E*	*C*	*I*	*Weight*
S	(1,1,1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(2, 3, 4)	0.01
E	(2, 3, 4)	(1,1,1)	(1,1,1)	(4,5,6)	0.30
C	(6,7,8)	(1,1,1)	(1,1,1)	(4,5,6)	0.58
I	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1,1,1)	0.11

Table 13: Metric values with respect to SD

SD	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.22
E	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)	(4,5,6)	0.26
C	(6, 7, 8)	(6, 7, 8)	(1, 1, 1)	(6, 7, 8)	0.26
I	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.26

Table 14: Metric values with respect to PF

PF	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(2, 3, 4)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	0.17
E	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	0.32
C	(6, 7, 8)	(6, 7, 8)	(1, 1, 1)	(2, 3, 4)	0.32
I	(4,5,6)	(6, 7, 8)	(1/4, 1/3, 1/2)	(1, 1, 1)	0.18

Table 15: Metric values with respect to PB

PB	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(2, 3, 4)	(1/8, 1/7, 1/6)	(2, 3, 4)	0.01
E	(1/4, 1/3, 1/2)	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)	0.22
C	(6, 7, 8)	(1/4, 1/3, 1/2)	(1, 1, 1)	(6, 7, 8)	0.55
I	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.24

Table 16: Metric values with respect to LL

LL	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1/4, 1/3, 1/2)	0.12
E	(2, 3, 4)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	0.16
C	(1/4, 1/3, 1/2)	(6, 7, 8)	(1, 1, 1)	(4, 5, 6)	0.56
I	(2, 3, 4)	(2, 3, 4)	(1/6, 1/5, 1/4)	(1, 1, 1)	0.17

Table 17: Metric values with respect to BP

BP	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	0.09
E	(4, 5, 6)	(1, 1, 1)	(1/4, 1/3, 1/2)	(4, 5, 6)	0.30
C	(6, 7, 8)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	0.57
I	(2, 3, 4)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	0.04

Table 18: Metric values with respect to DB

DB	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(6, 7, 8)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	0.18
E	(1/8, 1/7, 1/6)	(1, 1, 1)	(1/6, 1/5, 1/4)	(4, 5, 6)	0.11
C	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)	(6, 7, 8)	0.49
I	(4, 5, 6)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.11

Table 19: Metric values with respect to SM

SM	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(2, 3, 4)	0.02
E	(6, 7, 8)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.23
C	(2, 3, 4)	(6, 7, 8)	(1, 1, 1)	(4, 5, 6)	0.59
I	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1, 1, 1)	0.16

Table 20: Metric values with respect to VM

RM	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(6, 7, 8)	0.27
E	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)	0.27
C	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/6, 1/5, 1/4)	0.41
I	(1/8, 1/7, 1/6)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)	0.05

Table 21: Metric values with respect to CM

CM	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)	(4, 5, 6)	0.09
E	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(4, 5, 6)	0.45
C	(6, 7, 8)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/4, 1/3, 1/2)	0.45
I	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(2, 3, 4)	(1, 1, 1)	0.02

Table 22: Metric values with respect to RM

VM	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(2, 3, 4)	0.16
E	(4, 5, 6)	(1, 1, 1)	(1/6, 1/5, 1/4)	(6, 7, 8)	0.30
C	(2, 3, 4)	(4, 5, 6)	(1, 1, 1)	(6, 7, 8)	0.41
I	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.12

Table 23: Metric values with respect to CO

CO	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(6, 7, 8)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	0.20
E	(1/8, 1/7, 1/6)	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	0.02
C	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)	(6, 7, 8)	0.49
I	(4, 5, 6)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.29

Table 24: Metric values with respect to RP

RP	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(6, 7, 8)	0.21
E	(2, 3, 4)	(1, 1, 1)	(4, 5, 6)	(1/4, 1/3, 1/2)	0.27
C	(6, 7, 8)	(1/6, 1/5, 1/4)	(1, 1, 1)	(2, 3, 4)	0.35
I	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1, 1, 1)	0.17

Table 25: Metric values with respect to CU

CU	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	0.09
E	(4, 5, 6)	(1, 1, 1)	(1/4, 1/3, 1/2)	(4, 5, 6)	0.37
C	(6, 7, 8)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	0.50
I	(2, 3, 4)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	0.04

Table 26: Metric values with respect to CT

CT	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(4, 5, 6)	(1/6, 1/5, 1/4)	(1, 1, 1)	0.07
E	(1/6, 1/5, 1/4)	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)	0.43
C	(4, 5, 6)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	0.43
I	(1, 1, 1)	(4, 5, 6)	(1/6, 1/5, 1/4)	(1, 1, 1)	0.07

Table 27: Metric values with respect to IE

IE	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/8, 1/7, 1/6)	(4, 5, 6)	(1, 1, 1)	0.13
E	(6, 7, 8)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	0.24
C	(1/6, 1/5, 1/4)	(6, 7, 8)	(1, 1, 1)	(1/6, 1/5, 1/4)	0.47
I	(1, 1, 1)	(4, 5, 6)	(4, 5, 6)	(1, 1, 1)	0.16

Table 28: Metric values with respect to CH

CH	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(2, 3, 4)	0.02
E	(6, 7, 8)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.23
C	(2, 3, 4)	(6, 7, 8)	(1, 1, 1)	(4, 5, 6)	0.59
I	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1, 1, 1)	0.16

Table 29: Metric values with respect to CF

CF	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1, 1, 1)	0.23
E	(2, 3, 4)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	0.19
C	(6, 7, 8)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	0.40
I	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1, 1, 1)	0.19

Table 30: Metric values with respect to IS

IS	*S*	*E*	*C*	*I*	*Weight*
S	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	0.09
E	(4, 5, 6)	(1, 1, 1)	(1/4, 1/3, 1/2)	(4, 5, 6)	0.37
C	(6, 7, 8)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	0.50
I	(2, 3, 4)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	0.04

Step 8: Final weight for combination mode is estimated as (see Table 31):

$$\{0.08*(0.42) + 0.43*(0.53) + 0.04*(0.47) + 0.20*(0.45) + 0.24*(0.46)\} = 0.51$$

The highest score in Table 31 provides the best mode. According to the final score combination mode is the most preferred mode for development phase. The final weights of the different criteria show that the reusability is the most important criteria during development phase, followed by the intelligence, collaboration, final design and functionality.

Table 31: Final weights of alternatives with respect to overall goal

Criterion	Criterion weight	Sub-criterion	Sub-criterion weight	Alternatives			
				S	**E**	**C**	**I**
RE	0.08	**DD**	0.39	0.01	0.3	0.58	0.11
		SD	0.07	0.22	0.26	0.26	0.26
		PF	0.54	0.17	0.32	0.32	0.18
RA	0.43	**PB**	0.05	0.01	0.22	0.55	0.24
		BP	0.56	0.01	0.22	0.55	0.24
		LL	0.1	0.12	0.16	0.56	0.17
		DB	0.28	0.18	0.11	0.49	0.11
FT	0.04	**SM**	0.31	0.02	0.23	0.59	0.16
		RM	0.31	0.16	0.3	0.41	0.12
		CM	0.19	0.09	0.45	0.45	0.02
		VM	0.19	0.27	0.27	0.41	0.05
CO	0.2	**CO**	0.18	0.2	0.02	0.49	0.29
		RP	0.28	0.21	0.27	0.35	0.17
		CU	0.38	0.09	0.37	0.5	0.04
		CT	0.16	0.07	0.43	0.43	0.07
IN	0.25	**IE**	0.52	0.13	0.24	0.47	0.16
		CF	0.29	0.23	0.19	0.4	0.19
		CH	0.08	0.02	0.23	0.59	0.16
		IS	0.11	0.09	0.37	0.5	0.04
Final weight				0.13	0.2	0.51	0.16
Influence ranking				**4**	**2**	**1**	**3**

4.5.2 Comparative Analysis

This sub-section presents the comparative results in order to authenticate the robustness of the proposed EFAHP approach. A rigorous analysis is carried out to assess its performance and is confirmed by comparing the obtained results with that of from traditional fuzzy-AHP approach

(Table 32). The comparisons are conducted on the basis of the final ranking of SECI modes. The order of SECI modes changed when traditional fuzzy-AHP is applied because of zero value assigned to some of the sub-criterion when computing the degree of possibility. The result returned by application of traditional fuzzy-AHP approach contradicts the conclusions made by other authors in the literature (Madhavan and Grover, 1998; Schulze and Hoegl, 2005; McNally et al., 13). However, the result obtained using the EFAHP approach is consistent with past works and supports them.

Table 32: Comparison of ranking of SECI modes using different fuzzy-AHP method

Method / **Alternative**	**Fuzzy-AHP**	**EFAHP**
S	2	4
E	1	2
C	3	1
I	4	3

4.6 DISCUSSION

It is estimated in section VI that combination mode is important for the development phase. Combination mode essentially encourages maintaining expertise or technological knowledge at the enterprise level for a longer period. Collected reports issued by the internal and external agents (e.g., customer, competitor, partner, or government representative) are integrated, classified, reclassified, and synthesized with various existing explicit notions possessed by employees, to form a cluster of organized knowledge resulting in ‘systemic explicit knowledge’. In this mode explicit knowledge mentioned in files, databases, networks, and reports is transformed into intricate and organized explicit knowledge to identify innovative products or technologies most likely applicable to be put into practice. The potential medium for the combination mode include tools for systematizing knowledge, tools for collaborative computing, web forums, best practices databases, lists for discussion, and the intranet. The knowledge assets are systemized and packed documentation, manuals, specifications, database, patents and licenses. This dissertation proposes two visual lean tools for fostering the combination mode during development phase. This is owing to the fact that employees have to possess or learn an adequate understanding of each tool and concentrating on deploying a large number of tools can result in negative feedback from employees in terms of utilization. A higher number can draw less interest and lack of usage, which can lead to their banishment in the future. So the optimal number of tools/methods should be enforced to realize the maximum benefits.

Visual tool boards are a powerful way to create knowledge during the combination mode. A3 reports and spaghetti diagrams are two main examples of visual tools. An A3 report is only a single piece of A3 size paper that contains graphs and visual representations instead of large texts. Engineers synthesize, distil, and visualize the knowledge to put a large amount of both tacit and explicit knowledge into compressed form (Sobek and Smalley, 2008). They epitomize the old adage, "one picture is worth 1000 words," and make it easy for the user to comprehend the information. It helps in integrating and combining old explicit knowledge with new explicit knowledge in the combination mode.

A spaghetti diagram is a tool that indicates the value added and non-value added workflows using a continuous line in visual flow chart format. Traditionally, the lines are hand drawn and follow the workflow during observations. These lines may not be to the exact scale of the actual process. This is because the intention of the tool is to depict the flow of work or material in order to identify and eliminate any non-value-added movements. Improved knowledge creation in combination mode is supported by creative applications of computerized communication networks and large scale databases (Nonaka and Konno, 1998). These activities should be integrated with the deployment of good and proven practices or procedures, updating files, databases and website, relevant published research and reports to develop new policies and aims. It becomes a powerful tool when it is used with 5S initiatives (5S refers to a workplace organizational methodology based on: sort, systematize, shine, standardize, and sustain). The collected information should be referenced when developing rules, reports for decision-making.

Other practices that can be helpful in combination mode are project briefings, knowledge brokers, and selection of best practices. Project briefings can aid by involving the experienced team to provide knowledge and documents containing issues/results from previous projects. The new requirements can be combined with this knowledge by the current team. Generally, best practices can be considered as explicit knowledge if they are noted. They are proven approaches to handle repeating problems or processes effectively, and the documented information should be regarded as the major source of communications. Hence, functional specifications of new projects convoluted with explicated experiences or documents from the prior projects results in concrete knowledge creation during the SECI combination mode. The other modes don’t have any influence on the development phase so using tools that falls under those modes may not have adverse effect on the underlying phase.

CHAPTER 5. CONCLUSIONS

5.1 SUMMARY OF RESEARCH

This research discusses the associated problems with product development process for a case study unit of a Gas Turbine manufacturer. Drawing from the experiences and best practices of reviewed case study, the practical strategies are described to improve product development performance achieving lean goals such as improved quality, reduced waste and shortened PD lead-time. Specifically, Value Stream Mapping based method is used to develop the current state map in order to find the wastes in the process and action plan to eliminate all the wastes to reach the future (better) state. In order to develop the current state, a Gemba walk is done in order to find the most complex and lengthy lead-time process targeted for improvement. Consequently, a brain storming session is conducted to find out the root causes of wastes. The framework is still in the implementation phase, however, the expected benefits are summarized. All the proposed changes will result in the reduction of lead time for the design stage reducing thus the overall PD lead time by 50%.

In essence, the dissertation next investigated how lean tools and methods can facilitate efficient knowledge creation for the organizational learning. Dynamic knowledge paves the way for innovation and, thus, contributes in the growth of an organization. In order to describe a practical knowledge creation process, an integrated dynamic knowledge model made up of SECI modes, 'ba,' and knowledge assets has been targeted. With a view to improve the efficiency of the knowledge creation process in this model, a set of ten lean tools and methods is presented. Efficient knowledge creation not only decreases the magnitude of knowledge gaps, and assists future projects to start from a higher level of knowledge but also helps in making the right decisions quickly for faster and improved quality products. It also assists in reducing costly rework at the back end of the process by creating knowledge at the right time and right place. It is also stressed that simply implementing lean tools and methods is not the ideal solution for their sustainment and effective utilization, rather a strong lean mindset that fits into the organizational culture is important. Additionally, successful implementation requires organization-wide changes to systems, practices, and behaviours. One of the findings of this analysis is that Scrum, PDCA, and the 5 Whys can fit and support knowledge creation in more than one SECI modes.

This is the first attempt to conduct a numerical analysis in order to rank the influence of SECI modes on the development phase. For the numerical analysis, an EFAHP approach is proposed to properly analyze the decision variables of higher uncertainty and risks. SMEs expertize is exploited in deciding the criteria and sub-criteria to make the solution industry specific. In order to match a TFN for a specific scenario in the EFAHP (when two triangles are not intersecting), application of a normal distribution is proposed. This assisted us in developing a mathematical formulation to estimate the degree of possibility of two criteria as opposed to zero resulted by the use of the current technique in the literature. As a result, true priority weight of each alternative is calculated. During analysis, it is concluded that combination mode has the most effect on the considered phase. The conclusions drawn from present research after applying EFAHP are in accordance with that of found in the literature. However, application of traditional fuzzy-AHP approach contradicts them. The robustness of proposed method is authenticated thereby proving its superiority on the concerned problem. Right ranking of knowledge creation modes helps the development team to make informed-strategic decisions in selecting the relevant lean tools and methods to improve the performance. Such readily available information can play an important role in quickly bringing and expanding the product horizons.

5.2 OPPORTUNITIES FOR FUTURE WORK

Following are the topics which can be considered for future research.

- Implementation of VSM for a product family which has variable duration of each steps and validation of future state results using an interactive virtual reality simulation.
- Implementation of other innovative methodologies such as Critical Chain Project Management in product development with a view to reduce the lead-time.
- In addition, the extension of VSM implementation to other critical processes and finally to whole enterprise can be targeted in the future.
- Investigation of the human element factor in analyzing the performance of future state process.
- A framework exploiting the knowledge generated during process walk to store, retain and re-use is a potential research domain.
- The development of an evaluation model to estimate the improvements in product development performance resulting from knowledge creation or ranking of SECI modes on a specific product development phase.
- Application of EFAHP approach or some other powerful approaches to other product development phases such as concept design can also provide some interesting insights.

REFERENCES

Abdullah, F., 2003. Lean manufacturing tools and techniques in the process industry with a focus on steel. Doctoral dissertation, University of Pittsburgh, PA, USA.

Agarda, B., Bassetto, S., 2013. Modular design of product families for quality and cost. International Journal of Production Research 51 (6), 1648-1667.

Alavi, M., Leidner, D.E., 2001. Review: Knowledge management and knowledge management systems: Conceptual foundations and research issues. MIS Quarterly 25(1), 107–136.

Anand, G., Kodali, R., 2008. Development of a conceptual framework for lean new product development process. International Journal of Product Development 2(6), 190-224.

Anderson, D.M., Pine, J.B., 1997. Agile product development for mass customization. Irwin Professional Publishing, Chicago, USA.

Andreeva, T., Ikhilchik, I., 2011. Applicability of the SECI model of knowledge creation in Russian cultural context: Theoretical analysis. Knowledge and Process Management 18(1), 56–66.

Ardichvili, A., 2008. Learning and knowledge sharing in virtual communities of practice: motivators, barriers, and enablers. Advances in Developing Human Resources 10(4), 541–554.

Ballard, G., Howell, G.A., 2003. The underlying theory of project management is obsolete. Proceedings of the PMI Research Conference 293-302.

Bamford, D.R., Lodge, A., 2007. Health service improvement through diagnostic waiting list Management. Leadersh Health Serv 20 (4), 254-65.

Barczak, G., Kahn K.B., 2012. Identifying new product development best practice. Business Horizons 55 (3), 293-305.

Baek, S., Lim, G., Lee, D., Lee, J., 2008. Exploring factors that affect the usage of KMS: Using log data analysis. Knowledge Management Research 12, 21 –42

Blankenburg, D., Kristensen, K., Aasland, K.E., Sivertsen, O.I., 2013. Virtual obeya: collaborative tools and approaches to boost the use of simulators in concept. In ECMS (163-169).

Boisot, M., 1999. Knowledge assets. Securing competitive advantage in the information Economy. Oxford, UK: Oxford University Press.

Bottger, P.C., Yetton. P.W., 1987. Improving group performance by training in individual problem solving. Journal of applied Psychology 72 (4), 651-657.

Bratianu, C., Orzea, I., 2010. Organizational knowledge creation. Management, Marketing Challenges for Knowledge Society 3, 41-62.

Buranathiti, T., Cao, J., Chen, W., 2004. A weighted three-point-based strategy for variance estimation. In ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 637-645).

Cai, X., Tyagi, S.K., Yang, K., 2011. Activity-based costing model for MGPD. Improving Complex Systems Today 409-416.

Cai, X., Tyagi, S., 2014. Development of a product life-cycle cost estimation model to support engineering decision-making in a multi-generational product development environment. Journal of Cost Analysis and Parametrics 7(3), 219–235.

Cankurtaran, P., Langerak, F., Griffin, A., 2013. Consequences of new product development speed: A meta-analysis. Journal of Product Innovation Management 30 (3), 465–486.

Chan, F.T.S., Kumar, N., Tiwari, M.K., Lau H.C.W., Choy, K.L., 2008. Global supplier selection: a fuzzy-AHP approach. International Journal of Production Research 46(14): 3825–57.

Chan, Y.S. Greenbaum, S.I. Thakor, A.V., 1986. Information reusability, competition and bank asset quality. Journal of Banking and Finance 10(2), 243-253.

Chang, D.Y., 1996. Applications of the extent analysis method on fuzzy AHP, European Journal of Operational Research 95(3), 649–655.

Chen, C.T., Lin, C.T., Huang, S.F., 2006. A fuzzy approach for supplier evaluation and selection in supply chain management. International Journal of Production Economics 102(2), 289-301.

Cheng, E.W.L, Li H., 2001. Information priority setting for better resource allocation using analytic hierarchy process (AHP). Information Management and Computer Security 9(2), 61–70.

Choi, B., Lee, H., 2002. Knowledge management strategy and its link to knowledge creation process. Expert Systems with Applications 23(3), 173-187.

Clark, K.B., Fujimoto, T., 1991. Product development performance: Strategy, organization and management in world auto industry. Harvard Business School Press, Cambridge, MA.

Chatenier, E.D.,Verstegen, J., Biemans, H., Mulder, M., Omta, O., 2009. The challenges of collaborative knowledge creation in open innovation teams. Human Resource Development Review 8(3), 350-381.

Cooper, R.G., Edgett, S.J., and Kleinschmidt, E.J., 2003. Best practices in product innovation: what distinguishes top performers. Hamilton, Ontario: Product Development Institute.

Cortada J., Woods J., 1999. The knowledge management yearbook. Boston, MA: Butterworth-Heinemann.

Corti, E., Lo Storto, C. 2000. Knowledge creation in small manufacturing firms during product innovation: An empirical analysis of cause-effect relationships among its determinants. Enterprise and Innovation Management Studies 1(13): 245-263.

Cudney E., Elrod, C., 2010. Incorporating lean concepts into supply chain management. International Journal of Six Sigma and Competitive Advantage 6 (1/2), 12-30.

Cusumano, M., Kahl, S., Suarez, F.F., 2012. Product, Process, and Service: A New Industry Lifecycle Model, StudyMode.com.

Darlington, M.J., Culley, S.J., 2004. A model of factors influencing the design requirement. Design Studies, 25(4), 329-350.

Date, H., Sinha, R.R. (2013). A comparative analysis of knowledge management process maturity models. International Journal of Innovative Research and studies, 2(5), 221-234.

Davenport, T., Prusak, L. 1998. Working knowledge. Cambridge, MA: Harvard Business School Press.

Demeter, K., Matyusz, Z., 2011. The impact of lean practices on inventory turnover. International Journal of Production Economics 133 (1), 154-163

Droge, C., Jayaram, J., Vickery, S.K., 2000. The ability to minimize the timing of new product development and introduction: an examination of antecedent factors in the NA automobile supplier industry. Journal of Product Innovation Management 17 (1), 24-40.

Dyer, J.S. 1990. Remarks on the analytic hierarchy process, Management Science, 36, 249-258.

Easa, N.F. (2012). Knowledge creation process and innovation in the Egyptian banking sector: Methodological aspects. 20th EDAMBA Summer Academy, Soreze, France.

Edenius, M., Borgerson, J., 2003. To manage knowledge by intranet. Journal of Knowledge Management 7(5), 124-136.

Esterhuizen, D., Schutte, C.S.L., Du Toit, A.S.A., 2012. Knowledge creation processes as critical enablers for innovation. International Journal of Information Management 32(4), 354-364.

Evered, R.D., Selman, J.C., 1989. Coaching and the art of management. Organizational Dynamics 18(2), 16-32.

Fahey, L., Prusak, L., 1998. The eleven deadliest sins of knowledge management, California Management Review 40(3), 275-276.

Farris, J. A., van Aken, E.M., Letens, G., Pimsinee C., Coleman, G., 2011. Improving the performance review process. International Journal of Operations and Production Management 31(4), 376-404.

Fleischer, M., Liker, J., 1997. Concurrent engineering effectiveness—integrated product development across organizations. Hanser Gardner Publications, Cincinnati, USA.

Frank, A., Echeveste, M., 2012. Knowledge transfer between NPD project teams: a method for the identification of improvement opportunities. International Journal of Quality and Reliability Management 29(3), 242-264.

Gabčanová, I., 2011. The employees – the most important asset in the organizations. Human Resources Management and Ergonomics (5)1, 30-33.

Goffin, K., Koners, U., 2011. Tacit knowledge, lessons learnt, and new product development. Journal of Product Innovation Management 28(2), 300-318.

Gold, A.H., Malhotra, A., Segars, A.H., 2001. Knowledge management: An organizational capabilities perspective. Journal of Management Information Systems 18(1), 185-214.

Hall, R., Andriani, P., 2002. Managing knowledge for innovation. Long Range Planning, 35, 29-48

Hammad A., Nikolaos, T., 2013. An exploration of new product development's front-end knowledge conceptualization process in discontinuous innovations, British Journal of Management 24(2), 245–263.

Hansen, M.T., 1999. The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits. Administrative Science Quarterly 44(1), 82-111.

Haque, B., James-moore, M., 2004. Applying lean thinking to new product introduction. Journal of Engineering Design Volume 15 (1), 1-31.

Herron, C., Braiden, P.M., 2006. A methodology for developing sustainable quantifiable productivity improvement in manufacturing companies. International Journal of Production Economics 104 (1), 143-153.

Hines, P., Francis, M. Found, P., 2006. Towards lean products life cycle management. Journal of Manufacturing Technology Management 17(7), 866–887.

Hoegl, M. Schulze, A., 2005. How to support knowledge creation in new product development: An Investigation of knowledge management methods. European Management Journal 23(3), 263-273.

Houlahan, C.J., 1994. Reduction of front-end loading of inventory: making the airframe industry lean through better inventory management. MIT, Cambridge, USA.

Huthwaite, B., 2004. The lean design solution. Institute for Lean Design, Mackinac Island, MI, USA.

Imai, K., Nonaka, I., Takeuchi, H., 1985. Managing the new product development process: How the Japanese companies learn and unlearn in the uneasy alliance. Harvard Business School Press, Cambridge, MA.

Johannessen, J. A., Olsen, B., 2010. The future of value creation and innovations: Aspects of a theory of value creation and innovation in a global knowledge economy. International Journal of Information Management 30(6), 502-511.

Kane, H., Ragsdell, G., Oppenheim, C., 2006. Knowledge management methodologies. The Electronic Journal of Knowledge Management 4(2), 141–152.

Kennedy, M.N., 2003. Product Development for the Lean Enterprise. Oaklea Press.

Kennedy, M., Harmon, K., Minnock, E., 2008. Ready, set, dominate. Richmond, VA: Oaklea Press.

Khalil, R.A., Stockton, D.J. 2010. Predicting the effects of cycle time variability on the efficiency of electronics assembly mixed-model, zero-buffer flow processing lines. International Journal of Computer Integrated Manufacturing 23(12), 1149-1157.

Kotler, P., 2003. Marketing management: analysis, planning, implementation and control. Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Krogh, G., Ichijo, K., Nonaka, I., 2000. Enabling knowledge creation: How to unlock the mystery of tacit knowledge and release the power of innovation. New York: Oxford University Press.

Kumar, M., Antony, J., Singh, R.K., Tiwari, M.K., Perry, D., 2006. Implementing lean sigma framework in an Indian SME: a case study, Production Planning and Control 17(4), 407–423.

Langerak, F., Hultink, E.J., 2005. The impact of new product development acceleration approaches on speed and profitability: lessons for pioneers and fast followers. IEEE Transactions on Engineering Management 52(1), 30-42.

Lee, H., Choi, B., 2003. Knowledge management enablers, processes, and organizational performance: An integrative view and empirical examination. Journal of Management Information Systems 20(1), 179-228.

Lee, W. B., Lau, H., Liu, Z. Z., Tam, S., 2001. A fuzzy analytic hierarchy process approach in modular product design. Expert Systems, 18(1), 32-42.

Leonard, D., Sensiper, S., 1998. The role of tacit knowledge in group innovation. California Management Review 40(3), 112-132.

Li, C.Y., Hsieh, C.T., 2009. The impact of knowledge stickiness on knowledge transfer implementation, internalization, and satisfaction for multinational corporations. International Journal of Information Management 29(6), 425-435.

Liebowitz, J. (2009). Knowledge management handbook. Boca Raton, FL: CRC Press.

Lin, J., Qian, Y. Cui, W., Goh, T.N., 2015. An effective approach for scheduling coupled activities in development projects. European Journal of Operational Research 243(1), 97–108.

Lindlöf, L., Söderberg, B., Persson, M., 2012. Practices supporting knowledge transfer –an analysis of lean product development. International Journal of Computer Integrated Manufacturing 26(12), 1128-1135.

Liker, J., 2004. The Toyota way. New York, NY: McGraw-Hill.

Liu, M.S., 2012. Impact of knowledge incentive mechanisms on individual knowledge creation behaviour —An empirical study for Taiwanese R&D professionals. International Journal of Information Management 32(5), 442-450.

Li, Y.H., Huang, J.W., Tsai, M.T., 2009. Entrepreneurial orientation and firm performance: The role of knowledge creation process. Industrial Marketing Management 38(4), 440–449.

Locher, D., 2008. Value stream mapping for lean development: a how-to guide for streamlining time to market. New York, NY: Productivity Press.

Madhavan, R., Grover, R., 1998. From embedded knowledge to embodied knowledge: new product development as knowledge management. The Journal of Marketing 62(4), 1–12.

Maffinn, D., Braiden, P., 2001. Manufacturing and supplier roles in product development. International Journal of Production Economics 69, 205-213.

Martin-de-Castro, G., Lopez-Saez, P., Novas-Lopez, J.E., 2008. Processes of knowledge creation in knowledge-intensive firms: Empirical evidence from Boston's Route 128 and Spain. Technovation 28(4), 222-230.

Martinez Leon, H.C., Farris, J., 2011. Lean product development research: Current state and future directions. Engineering Management Journal, 23(1), pp. 29-51.

Mascitelli, R., 2007. Lean product development guidebook-Everything your design team needs to improve efficiency and slash time-to-market. Northridge: Technology Perspectives.

Maylor, H., 1997. Concurrent new product development: an empirical assessment. International Journal of Operations and Production Management 17 (12), 1196–1214.

McManus, H.L., 2005. Product development value stream mapping (PDVSM) manual. The Lean Aerospace Initiative, Cambridge, MA, USA.

McCauley-Bell, P. and Badiru, A.B. 1996. Fuzzy modeling and analytic hierarchy processing-means to quantify risk levels associated with occupational injuries. II. The development of a fuzzy rule-based model for the prediction of injury. IEEE Transactions on Fuzzy Systems 4(2), 132-138.

McNally, RC., Durmusoglu, SS., Calantone, RJ., 2013. New product portfolio management decisions: antecedents and consequences. Journal of Product Innovation Management 30(2), 245-261.

Meekings, A., 2005. Effective review meetings: the counter-intuitive key to successful performance measurement. International Journal of Productivity and Performance Management 54(3), 212-20.

Melon, M,G., Beltran, P.A., Cruz, M.C.G., 2008. An AHP-based evaluation procedure for Innovative Educational Projects: a face-to-face vs. computer-mediated case study. Omega 36(5):754–65.

Millson, M.R., Raj, S.P., Wilemon, D., 1992. A survey of major approaches for accelerating new product development. Journal of Product Innovation Management 9 (1), 53-69.

Morgan, J., Liker, J., 2006. The Toyota product development system: integrating people, process, and technology. Productivity Press, New York, USA.

Murphy, G., Salomone, S., 2013. Using social media to facilitate knowledge transfer in complex engineering environments: a primer for educators. European Journal of Engineering Education 38(1), 70-84.

Nevo, D., Chan, Y.E., 2007. A Delphi study of knowledge management systems: Scope and requirements. Information and Management 44(6), 583–597.

Nissen, M.E. 2006. Harnessing knowledge dynamics: principled organizational knowing, learning. London, UK: IRM Press.

Nguyen, T., Gordon-Brown, L., 2012. Constrained fuzzy hierarchical analysis for portfolio selection under higher moments, IEEE Transactions on Fuzzy Systems 20(4), 666-682.

Nonaka, A., 1994. Dynamic theory of organizational knowledge creation, Organization Science 5(1), 14-37.

Nonaka, I., Takeuchi, H., 1995. The knowledge-creating company: How Japanese companies create the dynamics of innovation. Oxford, UK: Oxford university press.

Nonaka, I., Toyama, R., Konno, N., 2000. SECI, Ba, and Leadership: A unified model of dynamic knowledge creation. Long range planning 33(1), 5-34.

Ohno, T. 1988. Toyota production system: beyond large-scale production. Cambridge, MA: Productivity Press.

Oinas-Kukkonen, H. 2005. Towards evaluating knowledge management through the 7C model. In Proceedings of the 12th European Conference on IT Evaluation (ECITE).

Oppenheim, B., 2004. Lean product development flow. Systems Engineering 7(4), 352–376.

Oshri, I., Kotlarsky, J., Willcocks, L.P. 2007. Global software development: Exploring socialization and face-to-face meetings in distributed strategic projects. Journal of Strategic Information Systems 16(1), 25–49.

Panizzolo, R., 1998. Applying the lessons learned from 27 lean manufacturers: The relevance of relationships management. International Journal of Production Economics 55(3), 223-240.

Parker, G.M., 2003. Cross-functional teams: Working with allies, enemies, and other strangers. John Wiley & Sons.

Pekgun-Cakmak, P., 2007. An analysis of pricing and lead-time policies within the marketing/ operations interface. PhD dissertation, Georgia Institute of Technology.

Pitt M., Clarke, K., 1999. Competing on competence: A knowledge perspective on the management of strategic innovation. Technology Analysis and Strategic Management 11(3), 301-316.

Pool, A., Wijngaard, J., Zee, D.J., 2011. Lean planning in the semi-process industry, a case study. International Journal of Production Economics 131(1), 194-203.

Popadiuk, S., Choo, C.W., 2006. Innovation and knowledge creation: how are these concepts related? International Journal of Information Management 26(4), 302-312.

Poppendieck, M., Poppendieck, T., 2007. Lean Software Development: An Agile Toolkit. Addison-Wesley Professional, MA, USA.

Quinn, T.D., 2012. The implementation dynamics of continuous improvement throughout the corporate hierarchy based on lean six sigma at DTE energy. MIT, MA, USA.

Radeka, K., 2012. The mastery of innovation: a field guide to lean product development. CRC Press.

Radnor Z., Boaden, R., 2008. Lean in Public Services—Panacea or Paradox?, Public Money & Management 28 (1), 3-7.

Rapp, W.V. 2000. Automobiles: Toyota motor corporation -gaining and sustaining long-term advantage through information technology. Sloan Foundation Project, NY.

Roemer, T.A., Ahmadi, R., Wang, R.H., 2000. Time-cost tradeoffs in overlapped product development. Operations Research 48 (6), 858-865.

Russell. R.S., Tuylor. B.W.. 1999. Operations Management. Prentice Hull: Upper Suddie River. NJ, USA.

Salmador, M. P., Bueno, E., 2007. Knowledge creation in strategy-making: Implications for theory and practice. European Journal of Innovation Management 10(3), 367-390.

Saaty, T.L., 1980. The Analytic Hierarchy Process, McGraw-Hill, New York, USA.

Schenkerman, S., 1994. Avoiding rank reversal in AHP decision support models, European Journal of Operational Research 74, 407-419.

Schneider, B. and Bowen, D.E. 1993. The service organization: human resources management is crucial. Organizational Dynamics, 21(4), 39-52.

Schulze, A. Hoegl, M., 2006. Knowledge creation in new product development projects. Journal of Management 32(2), 210.

Schultze, U., Stabell, C., 2004. Knowing what you don't know? Discourses and contradictions in knowledge management research. Journal of Management Studies 41(4), 549–573.

Seth, D., Gupta, V., 2005. Application of value stream mapping for lean operations and cycle time reduction: an Indian case study. Production Planning and Control 16 (1), 44-59.

Sethi, R.., Smith, D.C., Park C.W., 2001. Cross-functional product development teams, creativity, and the innovativeness of new consumer products. Journal of Marketing Research 38, 73–85

Shehab, A.A., Alam, E.R., Sopelana, A., Sorli, M., Flores, M., Taisch, M., Stokic, D., James-Moore, M., 2010. The Conceptual LeanPPD Model. ISPE International Conference on Concurrent Engineering. Cracow (Poland).

Singh, B., Garg, S. K., Sharma, S. K., 2011. Value stream mapping: literature review and implications for Indian industry. The International Journal of Advanced Manufacturing Technology 53(5-8), 799-809.

Simons, D., Taylor, D., 2007. Lean thinking in the UK red meat industry: A systems and contingency approach. International Journal of Production Economics 106 (1), 70-81.

Smith, P.G., 1999. Managing risk as product development schedules shrink. Research-Technology Management 42, 25-32.

Smith, P.G., Reinertsen, D.G., 1998. Developing products in half the time: New rules, new tools. John Wiley & Sons, New York, USA.

Sobek, D. Smalley, A., 2008. Understanding A3 thinking: a critical component of Toyota's PDCA management system. New York, NY: Productivity Press.

Storch R.L., Lim, S., 1999. Improving flow to achieve lean manufacturing in shipbuilding. Production Planning and Control 10 (2), 127-137.

Sullivan, W.G., McDonald, T.N., Aken, E.M., 2002. Equipment replacement decisions and lean manufacturing. Robotics and Computer Integrated Manufacturing 18 (3-4), 255–265.

Sutherland, J., Schoonheim, G., Kumar, N., Pandey, V., Vishal, S., 2009. Fully distributed scrum: Linear scalability of production between San Francisco and India. In IEEE Agile Conference, Chicago, USA.

Swan, J., Newell, S., Scarbrough, H., Hislop, D., 1999. Knowledge management and innovation: networks and networking. Journal of Knowledge Management 3(4): 262-275.

Syan, C.S., Menon, U., 1994. Concurrent engineering: concepts, implementation and practice. Chapman & Hall, New York, USA.

Tabucanon, M.T., Batanov, D.N. Verma, D.K., 1994. Intelligent decision support system (DSS) for the selection process of alternative machines for flexible manufacturing systems (FMS). Computers in Industry 25, 131-43.

Tham, K.M., Sharif, S.A., Kayis, B., 2006. Enterprise knowledge based database for new product development process. IEEE International Conference on Management of Innovation and Technology 1, 427-431

Towner, S. J., 1994. Four ways to accelerate new product development. Long Range Planning 27(2), 57-65.

Tyagi, S.K., Cai, X., Yang, K., Chambers, T, 2015 (a). Lean tools and methods to support efficient knowledge creation, International Journal of Information Management 35 (2), 204-214.

Tyagi, S.K., Choudhary, A., Cai, X., Yang, K., 2015 (b). Value stream mapping to reduce lead-time of a product development process. International Journal of Production Economics 160, 02-212

Tyagi, S.K., Ghorpade, A., Karunakaran, K.P., Tiwari, M.K., 2007. Optimal part orientation in layered manufacturing using evolutionary stickers-based DNA algorithm. Virtual and Physical Prototyping 2 (1), 3-19.

Tyagi, S.K., Yang, K., Verma, A., 2013. Non-discrete ant colony optimisation (NdACO) to optimise the development cycle time and cost in overlapped product development. International Journal of Production Research 51 (2), 346-361.

Tyagi, S.K., Yang, K., Tyagi, A., Dwivedi, S.N., 2011. Development of a fuzzy goal programming model for optimization of lead time and cost in an overlapped product development project using a Gaussian Adaptive Particle Swarm Optimization-based approach. Eng. Appl. of AI, 24(5), 866-879.

Tyagi, S.K., Yang, K., Tyagi, A., Verma A., 2012. A fuzzy goal programming approach for optimal product family design of mobile phones and multiple-platform architecture. IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews 42(6), 1519-1530.

Ulrich, K.T., Eppinger, S.D., 2000. Product Design and Development. McGraw Hill, Boston, USA.

Vaccaro, A., Veloso, F., Brusoni, S. 2009. The impact of virtual technologies on knowledge-based processes: An empirical study. Research Policy 38(8), 1278–1287.

Vadde, S., Zeid, A., Kamarthi, S.V., 2011. Pricing decisions in a multi-criteria setting for product recovery facilities. Omega 39(2), 186–93.

Van laarhoven, P.J.M. Pedrycz, W., A fuzzy extension of Saaty's priority theory. Fuzzy Sets and Systems, 1983, 11, 229–241.

Verma, A., Tyagi, S., Yang, K., 2014. Modelling and optimization of direct metal laser sintering process. The International Journal of Advanced Manufacturing Technology.

Voss, C.A., Blackmon, K., Hanson, P., Oak, B., 1995. The competitiveness of European manufacturing-a four country study. Business Strategy Review 6 (1), 1-25.

Wang G., Huang S.H., Dismukesa J.P., 2004. Product-driven supply chain selection using integrated multi-criteria decision-making methodology. International Journal of Production Economics 91(1), 1–15.

Wang, Y.M., Luo, Y. Hua, Z., 2008. On the extent analysis method for fuzzy AHP and its applications. European Journal of Operational Research, 186(2), 735-747.

Ward, A., 2007. Lean product and process development. Cambridge, MA: The Lean Enterprise Institute.

Wheelwright, S.C., Clark, K.B., 1992. Revolutionizing product development. The Free Press, New York, USA.

Wilde P., Murray P., 2009. The use of an Intranet System to Enhance Student Learning in an Eco-House Design Project. Transactions, 6(1), 4-17.

Womack, J., Jones, D., Roos, D., 1990. The machine that changed the world, Rawson Associates, New York, USA.

Womack, J.P., Jones, D.T., 2003. Lean thinking: Banish waste and create wealth in your corporation. Free Press, New York, USA.

Worley, J.M., Doolen, T.L., 2006. The role of communication and management support in a lean manufacturing implementation. Management Decision 44 (2), 228–245.

Xu Z., and Liao, H., 2014. Intuitionistic Fuzzy Analytic Hierarchy Process. IEEE Transactions on Fuzzy Systems 22(4), 749-761.

Yang, C.W., Fang, S.C., Lin, J.L., 2010. Organisational knowledge creation strategies: A conceptual framework. International Journal of Information Management 30(3), 231-238.

Yang, K. 2007. Voice of the Customer Capture and Analysis. McGraw-Hill Professional, New York, USA.

Yang (Mark), M.G., Hong, P., Modi, S.B., 2011. Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing firms. International Journal of Production Economics 129 (2), 251-261.

Yin, R., 2009. Case study research design and methods. London, UK: SAGE Ltd.

Yucheng, D., Wei-Chiang, H., Yingfeng, X. Yu, S., 2011. Selecting the individual numerical scale and prioritization method in the analytic hierarchy process: A 2-tuple fuzzy linguistic approach. IEEE Transactions on Fuzzy Systems 19(1), 13-25.

Yuen, K., 2014. Fuzzy cognitive network process: Comparison with fuzzy analytic hierarchy process in new product development strategy. IEEE Transactions on Fuzzy Systems 22(3), 597-610.

Zadeh, L.A., 1965. Fuzzy Sets. Information and Control,.8(3), 199-249.

Zhang, H.C., Yu, S.Y., 1997. An environmentally conscious evaluation/ design support tool for personal computers. Proceedings of IEEE International Symposium on Electronics and the Environment, San Francisco, CA, 131-136.

Zussman E., Zhou, M.A., 1999. Methodology for modeling and adaptive planning of disassembly processes. IEEE Trans. Robot Automation, 15 (1), 190-194.

ABSTRACT

LEAN THINKING FOR LEAD-TIME REDUCTION AND EFFICIENT KNOWLEDGE CREATION IN PRODUCT DEVELOPMENT DOMAIN

by

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There are many distinct differences between manufacturing process and Product Development (PD) process, so lean tools have to be customized to deliver results in the later domain. The main focus of this dissertation is to extend them to manage and improve the PD process in order to develop the product faster while improving or at least maintaining the level of performance and quality. For aforesaid purpose, value stream mapping (VSM) method is used to explore the wastes, inefficiencies, non-valued added steps in a single, definable process out of complete PD process. Besides numerous intangible benefits, VSM framework will help the development team to reduce the lead-time by over 50%. Next, a set of ten lean tools and methods is proposed in order to support and improve efficiency of the knowledge creation (KC) process. The approach establishes a KC framework in PD environment, and systematically demonstrates how these lean tools and methods conceptually fit into and play a significant role in enhancing the performance of KC process. Following this, each of them is analysed and appropriately positioned in a SECI (socialization-externalization-combination-internalization) mode depending

on the best fit. Quick and correct KC at the right time aids in further improving the development lead-time and product quality.

Such successful innovation is often associated with adoption and execution of all SECI modes within any PD phase. This dissertation attempts to argue with this general notion and to distinguish different PD phases' affinity corresponding to distinct SECI mode. In this regard, an extended Fuzzy Analytic Hierarchy Process (EFAHP) approach to determine the ranking in which any PD phase is influenced from SECI modes is proposed. In the EFAHP approach, the complex problem of KC is first itemized into a simple hierarchical structure for pairwise comparisons. Next, a triangular fuzzy number concept is applied to capture the inherent vagueness in linguistic terms of a decision-maker. This dissertation recommends mapping the triangular fuzzy numbers (TFNs) with normal distributions about X-axis when the pessimistic value of one TFN is less than the optimistic value of other TFN ($t_{23} \leq t_{11}$). This allows us to develop a mathematical formulation to estimate the degree of possibility of two criteria as opposed to zero resulted by the use of the current technique in the literature. In order to demonstrate the applicability and usefulness of the proposed EFAHP in ranking the SECI modes, an empirical study of development phase is considered. After stringent analysis, we found that the combination mode was the mode that highly influenced the development phase.

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- SK Tyagi, A Choudhary, X Cai, K Yang (2015) Value stream mapping to reduce the lead-time of a product development process, IJPE, 160, 202-212.
- SK Tyagi, K Yang, A Verma (2013) Non-discrete ant colony optimisation (NdACO) to optimise the development cycle time and cost in overlapped product development, International Journal of Production Research, 51 (2), 346-361
- SK Tyagi, K Yang, A Tyagi, A Verma (2012) A Fuzzy Goal Programming Approach for Optimal Product Family Design of Mobile Phones and Multiple-Platform Architecture, IEEE Transaction on Systems, Man, and Cybernetics, Part C: Applications and Reviews, 42(6), 1519-1530.