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3D Hybrid Model For New Product Development

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By

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DEDICATION

Dedicated to my aunts, Ms. Kasturi Sali, Dr. Annapurna Sali, Ms. Jaya Sali, and my mother, Ms. Maheshwari Munoli

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This thesis would not have been possible without the guidance of my advisor, Prof. Share, and I would like to express my deepest appreciation to him. I am grateful to him for agreeing take up the position of my advisor and for his advice, patience and many insightful lessons, discussions and suggestions we had over the past year. Prof. share is someone you will appreciate for his sincerity towards his work, I hope to match and incorporate his sincerity and honesty in my work as I step out of RIT.

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Abstract

Peter Thiel, in his book Zero to One, mentioned the importance of going from zero to one over one to infinity. The value of innovation and creating a unique product will always hold a higher value than doing something that has already been done. The author explains how the businesses that are unique or have very few competitors tend to be more successful when compared to businesses that offer similar services or products as offered by numerous other businesses. To achieve this edge over the contemporaries, there is a growing need to introduce new products to the market by exploiting new and futuristic technology. This idea is profitable for the company only if the product is introduced before any of its contemporaries, spending as less cost and resources possible and with the minimal risk factor. For most complex innovative products, the end goal is known but the form, process, and risks that will be encountered while achieving the end objective are unknown. It is important for a New Product Development (NPD) model to have a distinction between fundamental objectives and means objectives, which will help design objectives and solutions. While developing complex and innovative products, the company without a proper structure of development will end up spending a lot of time, money, and resources on tasks that will not lead them to the end goal. This proposal addresses these problems and proposes a possible solution; a structured model that is based on ideas of Suh's axiomatic design, Barry Boehm's Spiral model and Robert Cooper's Stage-Gate process. The proposed hybrid of these three processes is a model that accounts for customer attributes at each stage of its development and is structured and takes into consideration other aspects of innovative product development, such as risk, scheduling, cost, performance, and regulatory concerns.

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Chapter 1

1.1 Introduction

To satisfy the demand of introducing new and innovative products to the market in the shortest possible span of time, economically and with minimal risk, the companies are moving from current Product Development Models to new models that are more agile, flexible, and compliant to their company's structure and operations. There are various methods for developing and introducing complex new products to the markets; Stage-gate method, Spiral model, and Booz, Alan and Hamilton (BAH) model are some of the models that are still in use. These models address some or most aspects or phases of a New Product Development process, and a versatile structure can be derived from these models. A basic form of Stage-gate model is used in most of the manufacturing companies and studies conducted by independent researchers show that there have been improvements in the companies that have employed some form of stage-gate method.

The main drawback of the stage-gate method is that it is a linear process and it restricts iterative process flow when the product is complex and the designers and engineers must revisit the initial phases of design. The model does not deal with the discovery process and activities to create new ideas and structure and may limit out of the box thinking [Cooper, 2006]. This model mainly focuses on decision making on whether the project will be profitable to continue [Grönlund et al., 2010]. The spiral model was mainly developed for complex government software development products [Boehm, 1986], which are subjected to constant end user change. The model allows the developers to go back to the initial stage and check/alter the course of their action accordingly. Suh's axiomatic design theory is designed to provide a scientific basis for designing products, but does not address the managerial aspects, market, marketing and post development stages.

Chapter 2

2.1 Research Objective

Most models are limited to certain phases of product development and some have limitations which may not allow the engineers to easily navigate their way through it and develop a product specific to customer needs which is economic, with less risk, and in the least amount of time possible. Combining the three models mentioned in the introduction, this thesis is a proposal of a hybrid model that will have key concepts of all the three models and address all the systems/groups that will be a part of the product in development. This will be able to facilitate a scientific and logical way of designing an engineering system along with providing high level managers the information needed to make managerial decisions.

This model can be tested either by implementing it in a company developing a new and innovative product, or by conducting a survey with managers and high level management of different companies which produce innovative products, who have an eagle's eye view of the Product Development Process of the company.

2.2 Project aim, Rationale & Question

According to a study by [de Visser et al., 2010] of 155 U.S. firms that follow some form of NPD structure and manufacture products that are either radical or incrementally innovative are more successful than the ones that do not follow any form of NPD process. It was found that cross-functional structures are more effective in a radical NPD processes and have a significant positive impact on breakthrough innovation performance. According to this, this thesis aims at developing a very effective cross-functional NPD process. Many problems that arise during product development often can only be resolved through interdisciplinary cooperation [Sharafi et al., 2010]. I hope to strike a balanced degree of cross-functional integration required for a successful product development process [Gupta et al., 1986]. Existing models often do not cover areas like simultaneous development, PD Management [Sharafi et al., 2010]. This thesis will provide a solution in the form of a cross-functional NPD model that will possibly eliminate some or most of the process uncertainties and bottlenecks.

Chapter 3

3.1 Literature Review

3.1.1 Stage-Gate Model

Robert Cooper proposed the Stage-Gate process in 1988 to conceive, develop, and launch new products focusing more on business, management, and marketing than the technical side of the spectrum. The main idea behind this is to access the project at various development stages and decide whether it is feasible and profitable to continue the project. Since its introduction, the companies have adapted, modified, and improved it into a faster, leaner, and more effective tool. This new and improved model focuses on seven key principles [Cooper, 2006] [Cooper, 1994].

1. Customer focused: Conceiving new products that pack a "wow" factor is what is missing from most new products. But most companies are not capable of conceiving such products and are instead focused on tweaks, modifications, and extensions which have little competitive advantage. To create products with excitement factors, the entire development team - technical, marketing, and operations should collect the customer's unmet and unarticulated needs through interviews and interfacing with real customers. This firsthand need filters information that is often incorrect and biased taken by salespersons and product managers.

2. Front-end loading: Before starting any project, a brief fact-based market study, technical, and business assessment pays off. This homework yields just enough vital information for making decision regarding product development, and sufficiently defining the product and process.

3. Spiral development: Product definition may change at any point in the development phase due to numerous reasons, such as shift in the market, competitive product, or wrong interpretation by the development team. If the product development team does not adapt to these changes, the resulting product won't be right for the market. To avoid this, a continuous feedback method should be

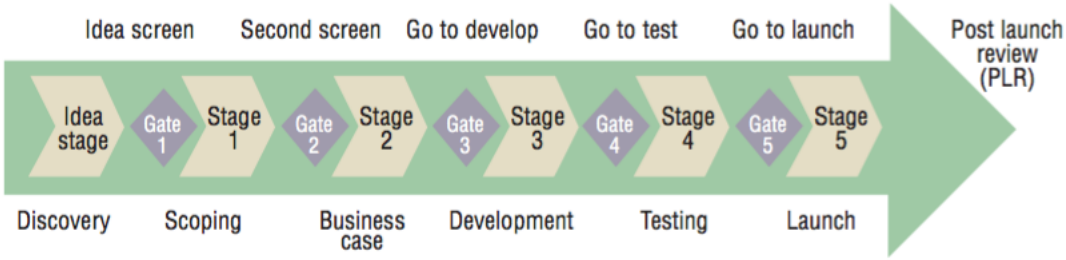

Figure 3.1: Stage-Gate model [Cooper, 2006]

followed. The feedback information will educate the team about the shift in the market or other developed changes in the product definition. These fast-paced teams remove unnecessary work and quickly move to finalized products, by forming a series of these iterative steps or loops: build, test, obtain feedback, and revise.

4. Holistic – effective cross-functional teams: Efficient and time driven projects always has a core team with effective cross-functional groups comprising of different effective players from different parts of the organization, who remain a part of the project from start to finish. It is the team leader's duty to steer the project to success in an entrepreneurial fashion.

5. Metrics, accountability, and continuous improvement: Defining a performance metric to measure the performance of the product they released is a profitable action. This metric will be specific to the company, the product released and the market of the product. A post launch gate review session will determine the results and the teams working on the project will be held accountable for either success or failure. It is a way of continuous learning and improvements in a development process.

6. Focus and portfolio management: Resource management is an important aspect of success. If a company has a lot of ongoing projects, they tend to fail to focus on individual projects and fail to allocate appropriate resources across all the projects. To counter this, an effective portfolio-management system will scrutinize and filter all the low-value projects.

7. Lean, scalable, and adjustable Stage-Gate process: Introducing a new Idea-to-launch procedure once every three years is a recommended activity. The key to a first-class idea-to-launch process are the six principles mentioned above.

The stage-gate process breaks down the innovation process into a predetermined set of stages. Each stage consists of a set of prescribed, cross-functional, and parallel activities. The entrance to each stage is a gate and these gates control the process and serve as quality control and GO/KILL check-points. The stages are defined by the activities within them, and there are usually standard or prescribed list of actions for each stage. Gates serve as quality control check points, GO/KILL, and prioritization decision points. At the gates, the action plan for the next stage is decided along with resource commitments. At each gate, the list of items to be achieved, resource allocation, scheduling, and budgeting anticipated for the next gate will be determined, and if the team is not able to achieve these expectations, then the top engineers and management will decide to either fund the project further and alter the functional attributes to tackle the risks or kill it because the risks far outweigh the benefits. This is one of the main features a Stage-Gate process brings into picture apart from giving the product development procedure a definite structure that will reduce the waste, time, cost and resources that would be wasted in-case the Stage-Gate model was not used.

The Stage-Gate model is based on the experiences, suggestions, and observations of large number of managers and firms and the author himself [Cooper, 2012]. The Stage-Gate model acts with the managerial and business needs but does not give enough room for the technical people to experiment and restricts innovation and learning opportunities and out of the box thinking and approach [Sethi and Iqbal, 2008]. Through the years, the idea of non-linear approach has caught on, and Lenfle and Loch have indicated a need to revisit the stage-gate approach [Nilsson and Wilson, 2012].

3.1.2 Spiral Model

The spiral model (see Figure 3.2), was a result of years of iterative refinements applied to the Waterfall model and was used to develop large government software projects. It can also accommodate most previous models as special cases and further provide guidelines to which combination of previous models best fits a given software [Boehm, 1986].

Each spiral begins with the identification of objectives, alternative means of implementation, and constraints imposed on the application of alternatives of the product being developed. The next step is to evaluate the alternatives relative to the objective and constraints. While doing so, the designers will stumble across areas of uncertainty and risks. If there are any risks, cost effective alternatives are developed to counter the risks and to test whether the feature/part is working, a prototype, simulation, benchmarking, reference checking and other techniques are employed.

The risk resolution stage is followed by dominating performance, user-interface risks, and/or internal-interface control risks. The next step will be an evolutionary development stage. In this stage, overall nature of the product and the next level of detailed prototyping will be determined to resolve risks further. Risk management considerations can determine the amount of time and effort to be devoted to other project activities like planning, quality assurance, formal verification, and testing.

Each cycle is completed by a review stage involving the lead designers and management concerned

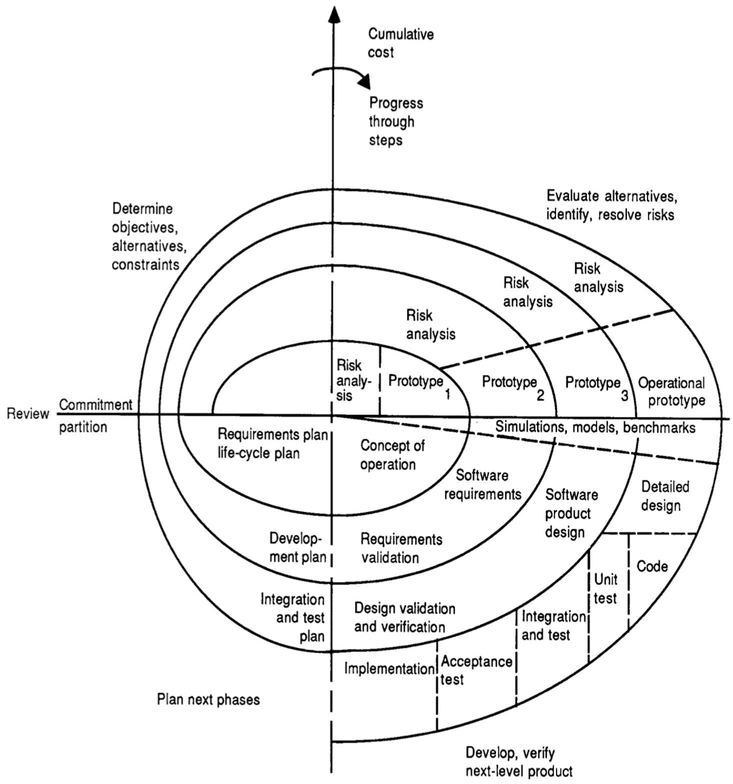

Figure 3.2: Spiral model [Boehm, 1986]

with the project. This review covers all the developments made in the previous cycle and the plans and resources for the next cycle.

Round 0: Feasibility study. A high-level objective and constraints list is generated and defined in qualitative terms. Alternative scenarios to the technology area like management, personnel, and facilities could lead in a decision to begin or scrap the project. Risk under Round 0 may be on high-leverage improvements and improving those risks may violate the constraints at this stage. Risk resolution activities under Round 0 will be surveys and analysis, structured interviews of development people and management. It will also answer basic feasibility questions and eliminate significant classes of candidate solutions.

Round 1: The level of investment is greater; objectives and constraints are more specific, additional constraints that emerge when the objectives are more detailed, alternatives will be more detailed, risks identified will be more specific, risk resolution activities will be more extensive and life cycle plan and plan for the next round which will be a more detailed step than the current round. This cycle will continue until the project is completed with all the objectives achieved and minimal constraint overlapping.

The Spiral model will accommodate for innovative approaches and out of the box thinking with its recurring risk assessment and management stages. It fosters the development of specifications that are not necessarily uniform, exhaustive or formal. It also accommodated rework or ability to go back to earlier stages when more appropriate alternatives are discovered at later stages. This kind of structure is very useful to develop a complex innovative product in any field.

However, there is no definite signboard that says that the project is no longer profitable and the risks far outweigh the benefits of continuing the project. The model has a definite structure for the development process but has no accommodation for any kind of software enhancements and maintenance that may come at any point through the life cycle of the software.

3.1.3 Axiomatic Design Theory

Axiomatic approach establishes a scientific foundation for the design field, so as to provide fundamental basis for creation of products, processes, system, software and organizations. Poor design practices result in high cost and long delivery times, which may be devastating to the firm. Part of the problem may arise from technical factors like continuing alteration of functional requirements, wrong design decisions, and the inability to recognize faulty decisions. Poorly designed products are more expensive, and are difficult to manufacture and maintain. Hence there is a need for a more rapid approach for the design than depending on trial and error, intuition and empiricism.

There are four main concepts in axiomatic design theory

1. Domains: There are four domains for each design activity and two parts to design, Functional domain and Physical domain. Customer attributes and objective of the design is shown in Functional domain and the physical solution to achieve the objective is shown in the Physical domain.

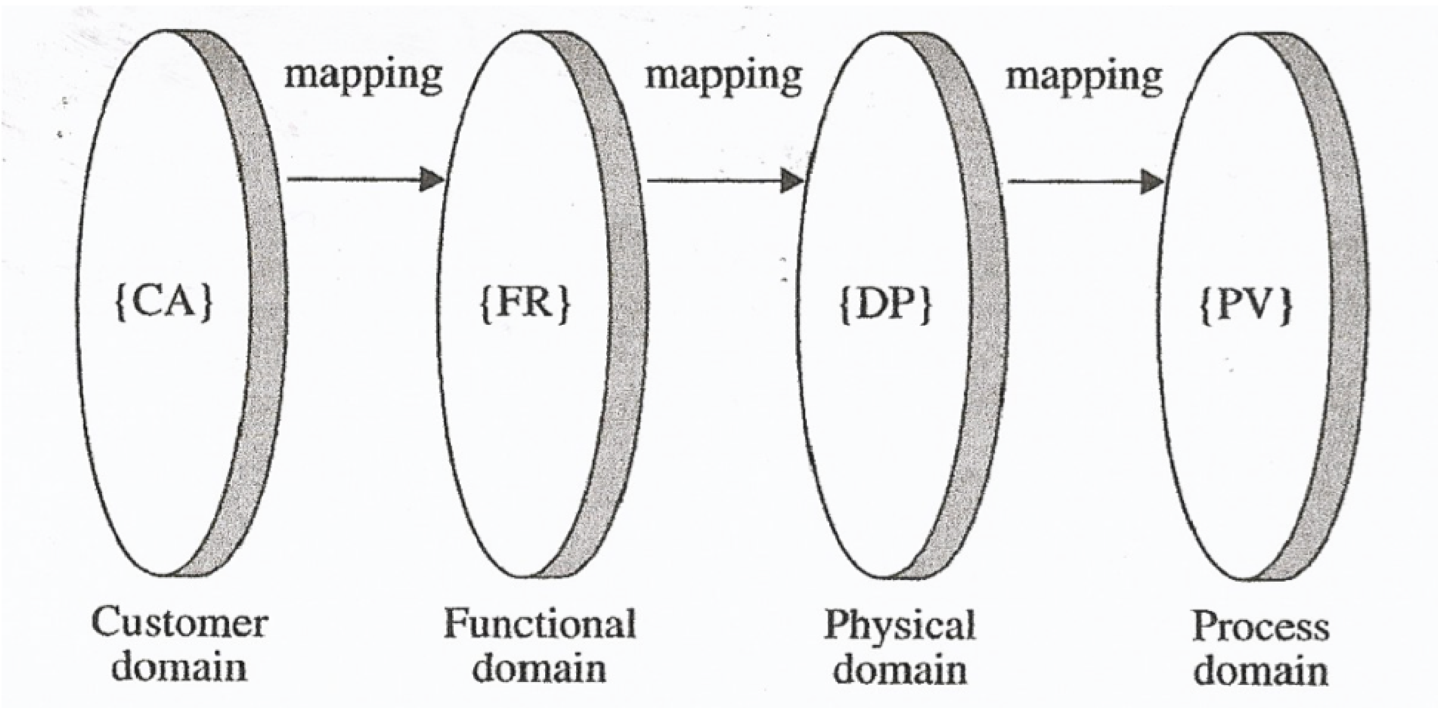

Figure 3.3: Domains of Axiomatic Design Theory (Google images)

(a) Customer domain: It gives us the customer requirements (CAs), what the customer is looking for in a product, technology, system or material. There are various methods of collecting customer requirements like, surveys, interviews, focus groups and so-on.

(b) Functional domain: Customer needs are translated into functional requirements (FRs) and constraints. A Functional Requirement can be defined as a minimum set of independent requirements that completely characterizes the functional needs of the product. Constraints can be defined as bounds on acceptable solutions. This is understanding and translating the customer needs into a technical language that can be further transformed into a product.

(c) Physical domain: Design parameters are conceived from the functional requirements to satisfy them and they can be defined as the key physical variables that characterize the design satisfying the specifies FRs.

(d) Process domain: To produce the design parameters, process variables are characterized which are developed in the process domain. The PVs can be defined as the key variables that characterize the process which can generate the specified DPs.

2. Mapping: The next step after creating the FRs of the functional domain is to map these into the physical domain - DPs. DPs chosen must not conflict with the constraints and they may be physical parameters or parts or assemblies in case of a products, modules or programs in case of a software. Once the DPs are chosen, designers must identify the process variables based on the creation of a new process or an existing process. Mapping is done efficiently within the decomposed levels by Zigzagging; The functional requirements in its highest level does not contain all the information to a successful end product. The FRs, DPs, and PVs must be decomposed until the design can be implemented without any further decomposition. The hierarchies of FRs, DPs, and PVs represent the system design and the decomposition of these can only be done through zigzagging between the domains. An example of Functional and Physical domain system design is shown in Figure 3.2.

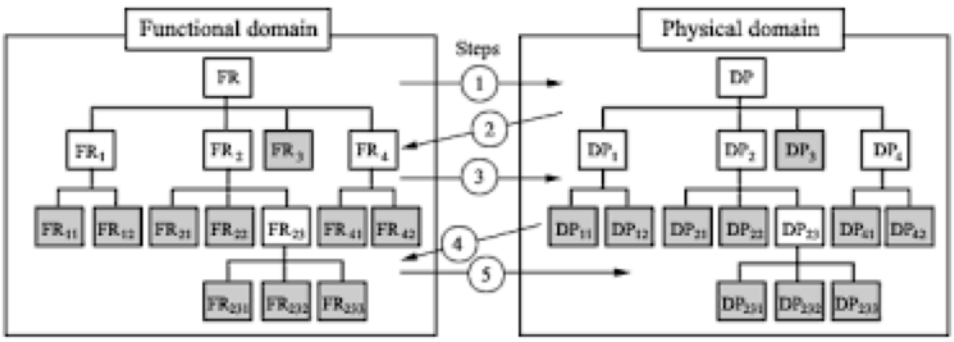

Figure 3.4: Zigzagging [Suh, 1998]

3. Design Axioms: Two axioms, that govern the design process, help to make a better decision while mapping DPs and PVs.

   - Axiom 1: The Independence Axiom. Maintain the independence of the Functional Requirements; The independence axiom states that when there are two or more FRs, the design solution should be such that each FR should be satisfied without affecting or conflicting the functionality of any other FR. We must think of different DPs for each FRs and select the one that is plausible. It is convenient to think about a specific DP for a given FR, but when there are many FRs, the design process becomes complex and finding a plausible DP that can satisfy as many FRs possible without violating the information axiom is a better solution than attributing 1 DP to 1 FR. The mapping process can be mathematically expressed in the form of a matrix

$$FR = [A]DP \tag{3.1}$$

     [A] is called the design matrix that relates FRs and DPs and characterizes the product design.

$$[A] = \begin{pmatrix} A11 & A12 & A13 \\ A21 & A22 & A23 \\ A31 & A32 & A33 \end{pmatrix}$$

     For the design to satisfy the independence axiom, the matrix [A] should be either diagonal, upper or lower triangular matrix. If the matrix [A] is a diagonal, it indicated that there is 1 DP for each FR and is called an uncoupled design. If it is triangular, the independence of FRs can be guaranteed only if the DPs are changed in order and is called decoupled design. All other matrix forms violate the independence axiom and are called uncoupled design.

   - Axiom 2: The Information Axiom. There can be many designs which are equally acceptable from the functional point of view. However, one of these designs may be superior to others in terms of probability of success in achieving the design goals as expressed by the functional requirements. The information axiom states that the design that has the least amount of information content is the best design. There is a need to quantify information, and information is related to complexity. To measure complexity, we need a rigorous definition. Consider I as the information content of the design, defined in terms of the probability (P) of satisfying a given FR. Then, the probability of I successfully satisfying a given FR can be mathematically written as

$$I = -log_2 p \tag{3.2}$$

In case of n FRs, for an uncoupled design, I may be expressed as

$$I = \sum_{i=1}^{n} \log \frac{l}{p_i}$$

[Park, 2007] [Suh, 1998]

Where pi is the probability of DP_i satisfying FR_i, and log is either logarithm based 2 or natural logarithm. The information in axiomatic design is defined as the logarithmic probability of satisfying the functional requirement. Information content is given by the tolerance specified by the designer and the tolerance the system can satisfy. Thus, the information associated with a given functional requirement is obtained by computing the probability or uncertainty of achieving the functional requirement. For a complex design with many decomposed levels, the information needed to satisfy the highest functional requirement, FR_i. The probability of success is given by the intersection of Resign Range (dr) and the ability of the system/machine to product the part within specified tolerance, i.e. System Range (sr). The graph explaining the above statement is as shown in Figure 3.4. Consider two functional requirements, FR_1 and

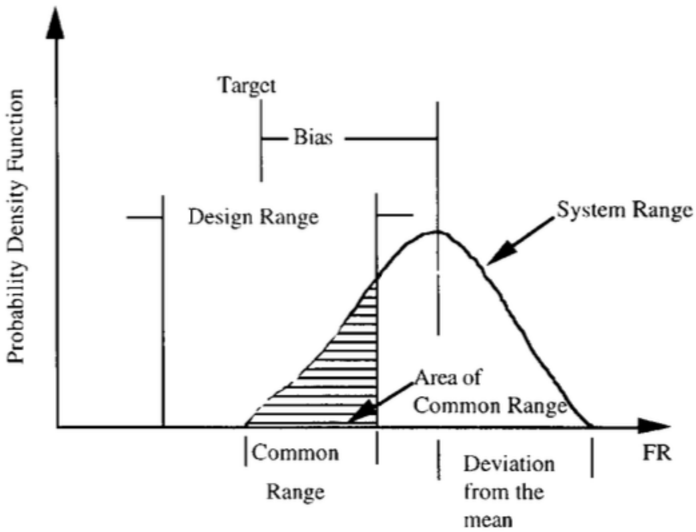

Figure 3.5: Graph of Probability Density Function vs Range [Park, 2007]

FR_2. In case of decoupled design, a solution DP1 will satisfy both the Functional Requirements. However, if there are two DPs, one for each FR, the information content is logically more. This may not be a good fit. For example, FR_1 = Design a device that can open bottles. FR_2 = Design a device that can open cans. The solution for this will be a bottle-can opener. Without physical integration, two pieces of the two DPs should be made. If we keep the amount of material constant, the sizes of each piece should be smaller. Then the use of each piece is inconvenient and the probability of success is reduced. The result is that the information content is increased.

Figure 3.6: Best design solution for bottle and can opener according to Information Axiom. (Google images)

Therefore, it is inferred that a tool with physical integration has less information content.

These axiomatic design principles, theories, and constraints are the scientific approach to any design process. However, the axiomatic design does not address managerial part of the project [Suh, 1998]. All these principles will be used and will be an integral part in proposing the new hybrid 3D model

3.1.4 Design for X

There is a constant need to make better decisions upfront, those, in particular, related to manufacturing and DFX provides designers tools to do it [Yang et al., 2009]. DFX is both philosophy and methodology that can help companies change and manage their product development activity. Designers and engineers will have many ways to design a particular product/component. The objective here is that, they select the option that will cost less to manufacture (fabricate), is robust, has less wastage, has a longer working lifespan and many other qualities that may apply to the product in design. In the early 1960s, several companies developed manufacturing guidelines for use during produce design [Kuo et al., 2001]. The X in DFX stands for manufacturability, inspectability, recyclability and any other 'bility' that might be applicable to the product in design [Huang, 1996]. 'Design' in DFX is interpreted as product design [Boothroyd et al., 2010]. DFX is used for the simple reason, and that is it works! The benefits of using DFX can be grouped in three categories

- Category 1: Benefits are directly related to competitive measures [Maskell, 1991], including improved quality, compressed cycle time, reduced life-cycle cost, increased flexibility and many more.
- Category 2: Benefits include improved and rational decisions in designing products, processes, and resources.
- Category 3: Benefits include effects on operational efficiency in product development. In general, DFX results in rationalization of decision-making and realization activities in designing products, processes and resources [Huang, 1996]

DFX has many tools that can be applied to a product development cycle of a new product at different sections. All the tools cannot be applicable at all the stages. The key "design for" activities to be tackled by the team are as follows:

- Use DFX as early as possible in the DFSS (Design for Six Sigma) algorithm
- Start with DFA and Design for Variety for product projects and Design for Service for Transactional projects
- From the findings of step 2, determine which DFX to use next. This is a function of DFSS team competence [Yang et al., 2009].

Some of the most common DFX tools that are most likely applicable to most product development processes are discussed below.

1. Design for assembly: This tool focuses on achieving the lowest assembly cost and ease of assembly. Boothroyd and Dewhurst have pioneered and developed the base of this tool and they have provided a handbook, "Product Design for Assembly" [Boothroyd et al., 2010]. This book indicates ratings for each part in the assembly, based on the part's east of handling and insertion. The idea is to minimize the cost of assembly within the constraints imposed by the other design features. The factors influencing assembly cost are 1. Total number of parts and 2. Ease of mating and handling these parts. Therefore, designers either reduce the number of parts by combining them or chose to avoid certain manufacturing/mating operations. The method developed by Boothroyd and Dewhurst is summarized as follows:

    - Each part designed is evaluated and a designer must validate and reason as to why the part cannot be eliminated or combined with other part. The idea is to reduce the number of parts.
    - A database of real-time standards is used as a reference for estimating assembly time.
    - A DFX index (design efficiency) is obtained by comparing the actual assembly time.
    - Assembly difficulties are identified which may lead to manufacturing and quality problems [Kuo et al.,

    Like Boothroyd and Dewhurst, there are other researchers who proposed alternatives and variants to satisfy the following criteria [Corbett, 1991]:

    - Minimize the number of (1) parts and fixtures, (2) design variants, (3) assembly movements, and (4) assembly directions

- Provide (1) suitable lead-in chamfers, (2) automatic alignment, (3) easy access for locating surfaces, (4) symmetrical parts, or exaggerate asymmetry, and (5) simple handling and transportation.
- Avoid (1) visual obstruction, (2) simultaneous fitting operations, (3) parts which will tangle or 'nest', (4) adjustments which affect prior adjustments, and (5) possibility of assembly errors.

2. Design for Manufacturing: Another huge aspect of product design is material selection and how to machine it. The DFM tool will address processes such as, raw material selection, process (machining) selection, modular design, standard component usage, multi-use part development, fastener usage and many more. Like DFA, researchers have various proposed tools to help facilitate the designers perform DFM in the best way possible. Kirkland, [Kirkland, 1988] provided factors that influence a designer's selection of material. (1) raw material selection, (2) process selection, (3) develop a modular design, (4) use standard components, (5) design parts to be multi-usable and so-on. Another researcher, Stoll, proposed a checklist of DFM guidelines that represented a systematic and identified list of statements concerning good design practices. [Stoll, 1988] DFM approaches that comprises of the above listed and many other tools that may be applicable to the product in design are helpful in determining the cost estimation at early stages which is very crucial and used actively in the 3D model proposed in this paper.

Like the listed DFX there are many tools that will be applicable at different stages and a picture of stages and tools applicable is listed below [Yang et al., 2009].

X	DFX	Reference
Product or process		
Assembly	Boothroyd-Dewhurst DFA	O'Grady and Oh (1991)
	Lucas DFA	Sackett and Holbrook (1988)
	Hitachi AEM	Huang (1996)
Fabrication	Design for Dimension Control	Huang (1996)
	Hitachi MEM	
	Design for Manufacturing	Arimoto et al. (1993)
		Boothroyd et al. (1994)
Inspection and test	Design for Inspectability	Huang (1996)
	Design for Dimensional Control	
Material logistics	Design for Material Logistics	Foo et al. (1990)
Storage and distribution	Design for Storage and Distribution	Huang (1996)
Recycling and disposal flexibility	Design for Ease of Recycling	Beitz (1990)
	Variety reduction program	Suzue and Kohdate (1988)
Environmental repair	Design for Environmentality	Navichandra (1991)
	Design for Reliability and Maintainability	Gardner and Sheldon (1995)
Service		
Cost	Design for Whole Life Costs	Sheldon et al. (1990)
Service	Design for Serviceability	Gershenson and Ishii (1991)
Purchasing	Design for Profit	Mughal and Osborne (1995)
Sales and marketing	Design for Marketability	Zaccai (1994)
	QFD	This volume, Chap. 6
Use and operation	Design for Safety	Wang and Ruxton (1993)
	Design for Human Factors	Tayyari (1993)

Figure 3.7: Sample DFX tool kits and references [Yang et al., 2009]

Chapter 4

4.1 Proposed 3D Hybrid Model for New Product Development

Model outline: The 3D hybrid model will have four phases resembling the axiomatic design principles.

1. Need Cycle
2. Technology Solution Cycle
3. Design Solution Cycle
4. Manufacturing Solution Cycle

Each cycle has four quadrants that will cover the major aspects of a new product development process such as research, innovation, cost & scheduling, performance, test & validation, risk management, regulation, and environmental factors and each quadrant has a checkpoint at the end. Multiple cycles make up a spiral. The number of cycles that constitute each spiral will depend on the complexity level of the project, or until the information cannot be further decomposed. The project's status is evaluated at the checkpoint by the checkpoint auditor and a Go/No-Go decision is made based on the quadrant activity inputs received. The auditors will either make a Go (pass) decision if the reported activities are satisfactory or a No-Go decision is made and a list of alterations are generated. The No-Go case alterations will be on the main to-do list of the following level and the results of these activities will be evaluated by the auditors (resembling the Stage-Gate model). This process will continue until the checkpoint auditors are satisfied with the results of the quadrant activities. At the end of each checkpoint, the auditors will generate a list of deliverables that will be utilized by the people working in different cycles of the project as additional inputs (Zigzagging) or to alter the activities (No-Go cases) to match the proceedings of the project. The objectives at each checkpoint for different quadrants of the cycle are unique with unique set of checkpoint auditors. The 3D Hybrid Model starts at the Need Cycle and spirals through the cycle and quadrants (segments). Initially the requirements are all high level and as the process develops, the requirements are detailed (resembling the Spiral Model). A complete breakdown of the four cycles and quadrants are explained below.

4.2 Need Cycle

The main agenda of this phase is obtaining the customer requirements. Effective checkpoints are central to the success of a fast-paced new product process. Understanding customer needs accurately is a key element in the success of the product. The difficult part is fully understanding customer needs, and it is usually expensive and unsure process [Thomke and von Hippel, 2002]. Customer needs are often subtle, complex, and change fast. Customer requirement is a very high-level statement and may not include any technical, physical, or performance specifications. This phase may end after a single level(cycle) or go multiple levels(cycles), depending on the complexity or newness of the product. Comparatively, this cycle may have less cycles than the other three phases.

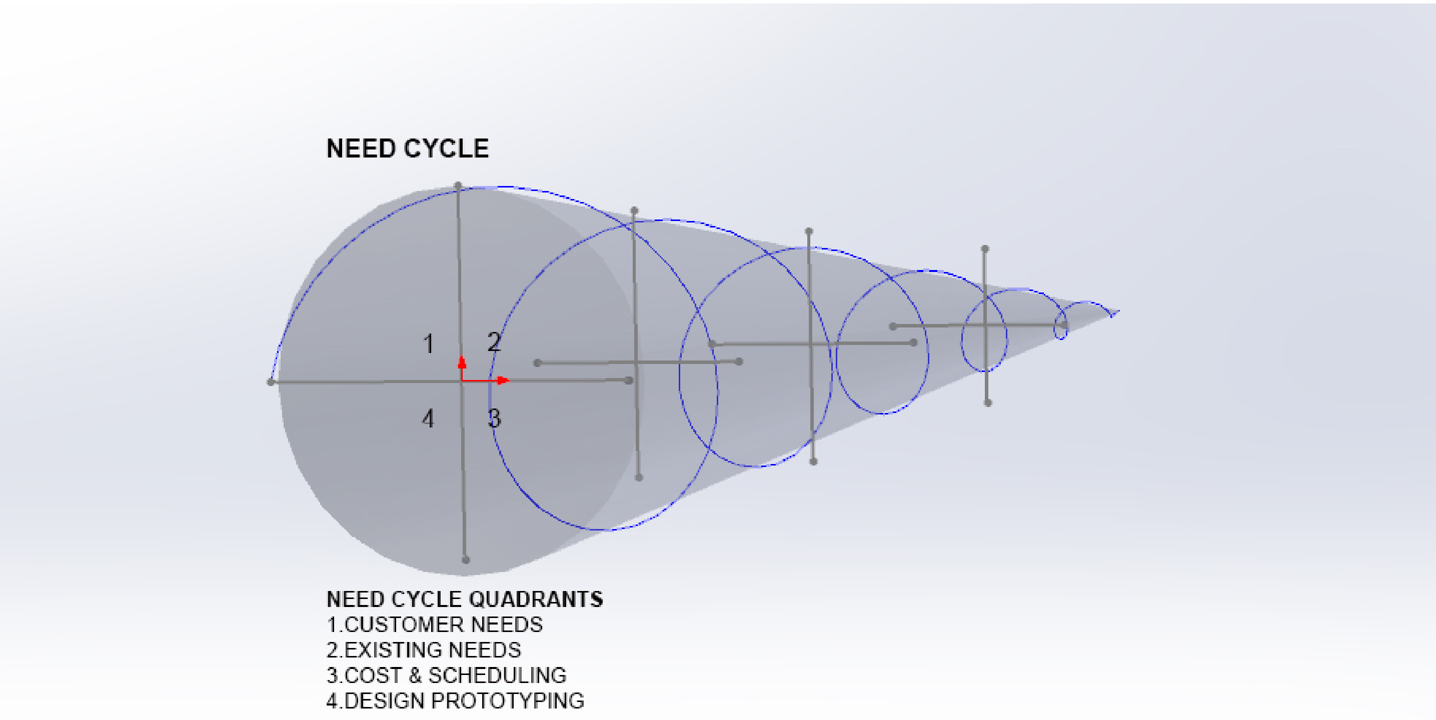

Figure 4.1: 3D Model for need cycle

4.2.1 Customer Needs Quadrant

In the first quadrant of the first cycle of this phase, high-level customer needs are collected. The customer needs are collected through either one or multiple sources, such as survey, ethnography, and personal interview. Based on these needs and with the inputs from the other quadrants, in case of levels grater than one, engineers identify and develop specific hidden needs. These needs are not specified by the customers and are requisites specified by the designers and the engineers at later cycles, based on their experience and knowledge, that are crucial in satisfying the actual customer needs. Engineers should be able to trace these developed hidden needs to the highest-level of customer needs.

- Needs checkpoint: The auditors will analyze the collected data and develop a consolidated need statement at each level. This forms a base for the next quadrant, where the engineers working on it will have a clear understanding of the customer needs. At cycles greater than 1, the auditors will trace developed hidden needs to the initial need statement and generate changes/deliverables list for the next cycle. The checkpoint auditors will be from marketing, engineering, and management.

4.2.2 Existing Needs Study Quadrant

Based on the developed customer need statement and developed hidden needs (in case of cycles greater than 1), a study is conducted to determine if there is any existing technology or product that satisfies the needs. If not, a high-level and non-technical solution is described that will satisfy the customer needs for the first cycle. As the spiral progresses, the same is repeated for the developed hidden needs at that point. The proposed solution or idea should satisfy the initial customer need.

- Technology checkpoint: This checkpoint will assess if the need specified or the solution described is feasible and in alignment with the main customer needs. If not, a request to alter the solution specific to the deliverables which is in sync with the high level customer needs created by the checkpoint auditors will be issued. The same activity will be repeated for the checkpoint activity at higher levels. The checkpoint auditors will be Engineering, Design, management and marketing teams.

4.2.3 Cost and Scheduling Quadrant

This quadrant will determine the resources and quantities required to fulfill the developed solutions. A conceptual cost estimate is developed by analogous estimation and expert judgment of the engineer and management members working in this quadrant. This section mainly helps the management to understand and prepare for the expenses and resources that will be required for the project. The Need Cycle ends before Technology Solution Cycle begins, this helps the management to make an informed decision based on the cycle activities whether the project is profitable to continue or whether the risks outweigh the benefits.

- Scheduling checkpoint: In the initial cycle of this checkpoint, auditors will document and assess the generated cost and scheduling reports. This will help make a Go/No-Go decision at the final level of the need cycle as all the cost and scheduling estimates developed will be available for evaluation. A Go/No-Go decision is made at each level based on the inputs received from the cost and scheduling quadrant. If a No-Go decision is made at any point, it indicates that the current status is dissatisfactory or incomplete. Various points are assessed at this checkpoint, such as cost, core capability of the company, scheduling activities, resources required, total time requirement of the project, and many others. The auditors will be Engineers, Designers, and management.

4.2.4 Designer Prototyping Quadrant

After the Technology checkpoint approves a research report satisfying certain customer needs, the designers generate a solution in the form of a prototype, CAD model, simulation model, or a description that will enable the engineers working in the future quadrants, cycles and phases to have a comprehensive need statement to work on. This quadrant also helps the engineers to understand and develop hidden customer needs in the following cycles. These hidden needs are the derivatives of customer needs. Customers cannot provide detailed list of needs and it is the job of the developers, engineers, and designers to develop requirements (hidden needs) necessary to satisfy the customer needs.

- Design checkpoint: At this checkpoint, the solutions generated at designer prototyping quadrant are documented and analyzed as a prequel for the next cycle of customer needs phase. These documentations also help support the information exchange throughout the product development process. The checkpoint auditors will be design engineers, marketing, and management.

Having this type of iterative process with customer and prototypes will slash the development time and costs substantially and eliminate the probability of misinterpretation of the customer needs by the engineers or errors that occur during the translation process [Thomke and von Hippel, 2002]

4.3 Technology Solution Cycle

Technology Solution Cycle starts after the Need Cycle ends. At this point the engineers will have a clear understanding of the customer requirements and other developed hidden needs. The next step is to understand, in technical language, what is needed to deliver the said requirements and needs. The documentation compiled in the design checkpoint of the need cycle will provide engineers a correct starting point. In this cycle, the engineers will have a very clear, precise, and in depth understanding of what needs to be produced (the end goal) and through-out this phase the team in charge will work with this set of requirements in mind. Similar to the Need Cycle, the Design Cycle will has four quadrants and the process spirals (Levels up) through quadrants and ends when an in-depth list of technical requirements, that will satisfy the initial highest cycle of customer requirement, are produced. i.e. spiral continues until no further decomposition is possible.

While defining the "what" i.e. translating the customer needs into technical language, the concept of core capability comes into picture [PRAHALAD and HAMEL, 1990]. To compete successfully, in the long term, firms focus on developing a limited set of distinctive core capabilities which would allow specialization and synergistic economics. Through these capabilities, the companies can deliver an ongoing flow of innovations to multiple markets [Grönlund et al., 2010]. The concept of core capabilities will help the managers decide what parts of the project needs to be outsourced so that the requirements are met with precision and on time. DFX tools that may be applicable (refer figure 5) at any of the four sections are used.

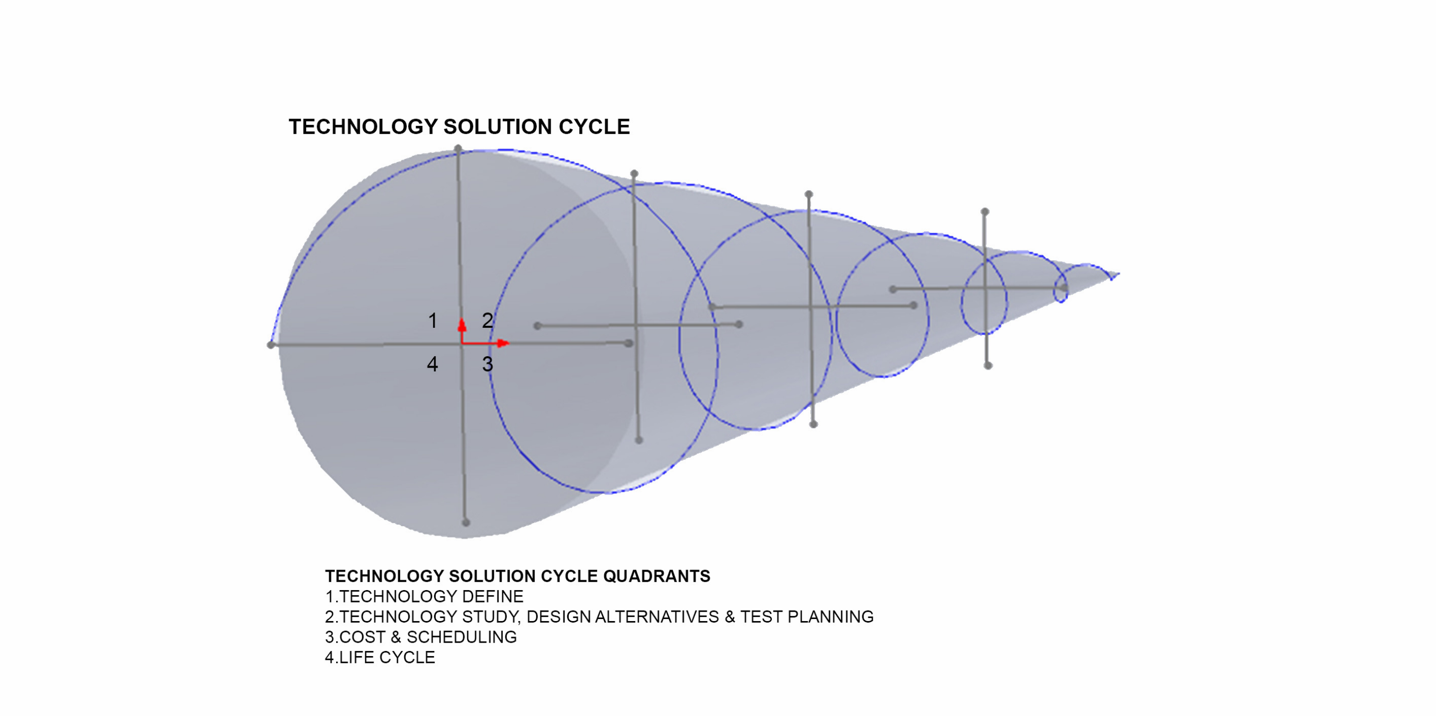

Figure 4.2: 3D Model for design cycle

The four sections and checkpoints for this cycle are explained below in detail.

4.3.1 Technology Define Quadrant

In the first quadrant of this cycle, the engineers and designers start working on the highest level of customer needs. Based on the documentation generated at the design checkpoint the translation of customer needs into technical requirements are carried out, i.e. they define "what". For the following cycles, the Technology Define Quadrant will get inputs from 2nd cycle Design Checkpoint of the Need Cycle and from the Design

Define Checkpoint (Zigzagging – Defined in the axiomatic design). These additional inputs received are the hidden technical requirements (Similar to the hidden needs).

- Define Checkpoint: In the first cycle, the checkpoint auditors will document all the technical requirements defined and this documentation acts like a to-do list for the following technology study & design alternative cycle. For the following cycles, this checkpoint keeps tabs of additional requirements received from define quadrant of physical cycle. These requirements will add on to the to-do list for the next cycle. The checkpoint auditors will check for the technical solution documentation and make a Go/No-Go decision for each translated technical solution. The changes required will be another input to the next cycle of Technology Define Quadrant. The checkpoints auditors will be high level Engineers and Designers.

4.3.2 Technology Study, Design Alternatives, and Test Planning Quadrant

Based on the technical requirements' to-do list developed at the previous checkpoint, the R&D team inspects the requirements and conducts research to provide specifications tailored to the required needs. Readily available products, technology, or materials may not be the best fit and may or may not satisfy the technical requirements. In case the existing solutions are not satisfactory, the R&D team will develop or propose modification/s to the existing products, technology or materials that will satisfy the requirements. The results of this quadrant are only as good as the team and its expertise. While researching about the said requirements, often, a lot of subcomponents that are vital for the functioning of the current requirements are discovered and these are further refined in the next cycle of Technology Define Quadrant as additional requirements. For example, consider a mobile phone's body. It is not a customer requirement to have a waterproof phone, but when the researchers think about the usage or functioning of a mobile phone, they can conclude that the functionality should not be affected by water. Hence, the researchers will add this as an additional requirement and all the components designed henceforth will be in compliance with the phone being waterproof. The proposed design requirements might not be a best fit in a system despite being the best fit individually (Suh's axioms). The engineers at this point, design and develop a test that will deem the design solution, developed in the Design Define Quadrant, a perfect fit. Acceptable test solutions for the above designed tests are developed, and these test solutions act as guidelines for developing design solutions at Design Define Quadrant. This stage provides a platform for engineers and designers to think out of the box and promotes innovative thinking and design. The existing or new selected technical requirements are altered to comply to the product in development. Once all the high-level design requirements and tests for a cycle are defined, Design Define Cycle (3rd Cycle) starts and the design solutions are drafted, i.e."how". After this quadrant, both Technology Design Cycle and Design Define Cycle run independently until the process spirals back (next cycle) to the Technology Define Quadrant.

- Technology checkpoint: The auditors will evaluate and document the technical solutions, additional functional requirements, test, and acceptable test solutions developed during this section. The concept of core capability comes into picture for making any decision at this checkpoint. The checkpoint auditors will decide based on their experience and knowledge, whether the company is capable of manufacturing a said component in house. Based on this evaluation, a decision is made whether the component should be altered, outsourced, or changed to match the core capability. In cycles grater than 1, the auditors will have an additional job of evaluating the additional requirements requested from the technology checkpoint of previous cycles. The checkpoint auditors will be Engineers, Research team, Designers, and High level management.

4.3.3 Cost and Scheduling Quadrant

After developing a list of specific technical requirements and a list of components that will be manufactured in house or outsourced, the resource planning team will generate an estimate of cost and the amount of resources, such as man power, raw materials, time, machines, and equipments required for in house production and acquire quotations for outsourcing activities. Based on these numbers, an analogous estimate will be developed and documented. In the later cycles, when almost all the requirements are known, a parametric modeling of a total cost budgeting is performed. This will act as a reference line for all the future activities.

- Scheduling Checkpoint: The reports generated in the initial cycles will be documented and assessed by the checkpoint auditors and a Go/No-Go decision is made. If there has to be an alteration in any of the cost or scheduling activities, this will be the deliverable in the next cycle of cost and scheduling section but the alterations may have to be made in the define or technology study sections. This documentation will help the future cycles prepare and provide resources for the activities. At the final cycle, the total cost budgeting report is analyzed and a final Go/No-Go decision is made on the project. This documentation will act as a reference line for all future cost and resource planning activities. The auditors will be Engineers, Designers, High level management.

4.3.4 Life Cycle Quadrant

The technology requirements selected are assessed for compliance with the legal laws and standards of the company. A life cycle assessment is made for every technology, material, process, or activity solution in question and a detailed report is generated. Designers will incorporate DFX tools applicable at this stage and alter the existing technological requirements accordingly to develop best possible results. The quadrant in cycle greater than one, may have deliverables in the form of a limitation, guidelines, or alteration request for materials, process, or technology solutions from the previous cycle's legal checkpoint. These deliverables will be addressed initially at the Technology Study, Design Alternatives, and Test Planning Quadrant and are again subjected to examination at this quadrant.

- Legal Checkpoint: This checkpoint will analyze the reports generated by the life cycle quadrant and a Go/No-Go decision is made by the auditors based on their expertise, knowledge, and requirements. If any alterations are required, these will be in the form of a limitation, guidelines, or alteration request for materials or processes or technology solutions. This alteration request will be issued to the Technology Study, Design Alternatives, and Test Planning Quadrant. Any alternatives in design solutions are generated at this quadrant. The checkpoint auditors will be Engineers, Designers, Legal team, and High level managers.

4.4 Design Solution Cycle

Design Solution Cycle starts after defining the technical requirements, tests and test solutions for the customer needs and additional hidden needs at the first cycle of Technology Solution Cycle. The next step is to define a design solution for the technical requirements. The technical requirements are given a form and designed to work in combination effectively and efficiently. This phase is similar to the previous phase, and has four quadrants and each quadrant ends in a checkpoint. The Design Solution Cycle and Technology Solution Cycle run almost simultaneous to one another, and by zigzagging there is an exchange of information between the two phases. If there are any changes performed in the Technology Solution Cycle, it is updated in the Design Solution cycle in the following cycle and vice versa. A detailed description about Design Solution Cycle and the zigzagging process is explained below.

4.4.1 Design Define Quadrant

This section receives its inputs from the Technology Study, Design Alternative, and Test Planning Quadrant. Once the highest level of technical requirements are listed, the engineers and designers at the Design Define Quadrant develop a design solution to satisfy the requirements. The parameters in the Design Solution Cycle are defined based on Suh's axioms. Suh promotes the decoupling of functional requirements in design. The independence of functional requirements allows design parameters to have a controllable effect on a specific functional requirement and minimal negative impact on other functional

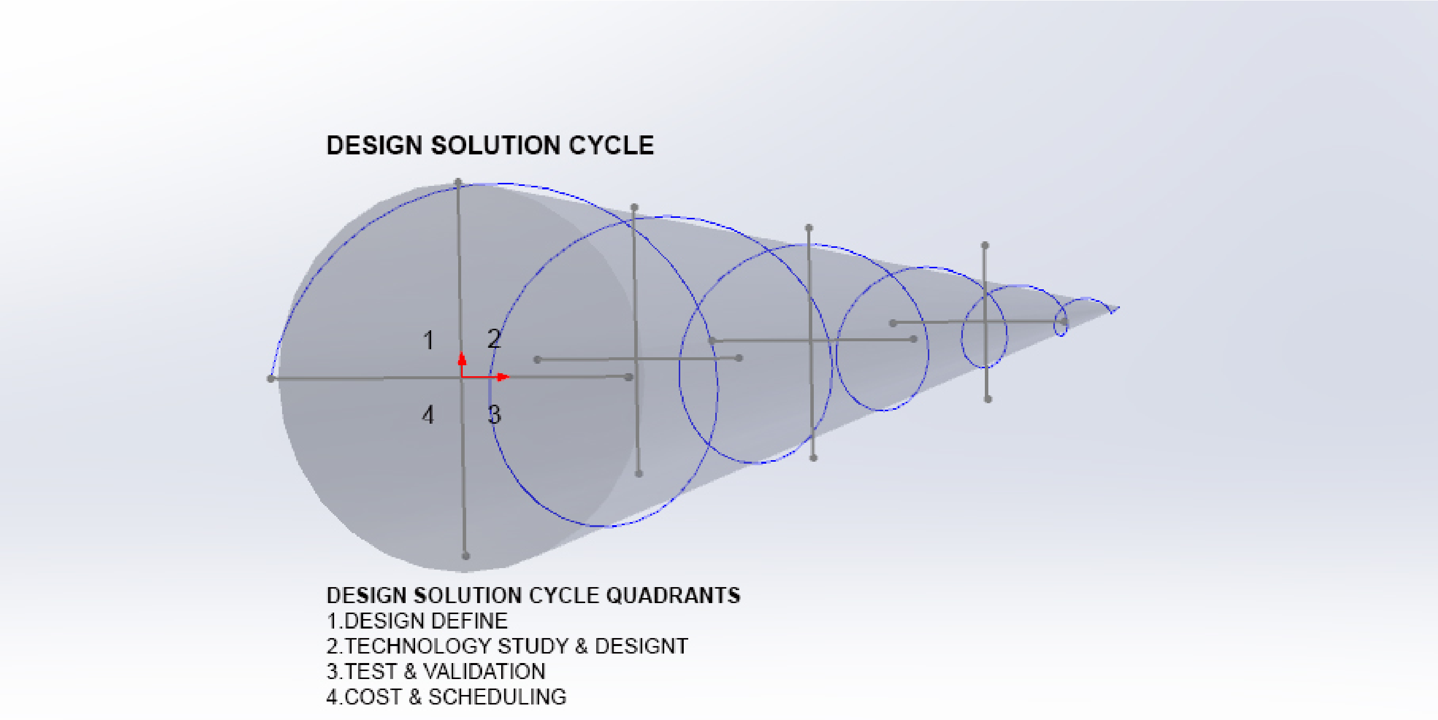

Figure 4.3: 3D Model for physical cycle

requirements [Suh, 1998] [Kuo et al., 2001]. In the higher cycles, similar activities are conducted and additional deliverables received from different stages (Quadrants and cycles) of the process are accommodated. The design solution can range from CAD designs, sketches, mathematical calculations, and prototype models applicable to the product in development.

- Define checkpoint: According to Suh's Independence Axiom, the design is labeled either coupled, decoupled, or uncoupled and the design solution should be either coupled or decoupled. According to Information Axiom, the design solution with the least information content is the best solution. The checkpoint auditors will analyze the design solutions provided based on Suh's principles and determine if the proposed solutions are feasible. Based on this, a Go/No-Go decision is made and a list of items that need to be changed for a No-Go decision are made. This list is shared with either the Technology Define Section define (zigzagging to next level) or Design Define Quadrant (deliverables at next level) based on the nature of alteration. The checkpoint auditors will be Sr. Engineers, Sr. Designers and Managers.

4.4.2 Technology study and Design Quadrant

After the design solutions are approved at the define checkpoint, a study is conducted to understand the design components and alter the design solutions specific to the requirements. These solutions will include the final description and specification of a component, sub-system, or system as a whole, depending on the cycle. For the development of these design solutions, the test solution requirements developed at the Technology Study, Design Alternative and Test planning Quadrant are considered to stay on track with the requirement specifications. During this study, if a new technology, material, or process is discovered that can be applied to the current design solution, and is better and effective in satisfying the technical requirements, that alternative is selected over the design solution suggested at the define quadrant. This quadrant provides an opportunity for the engineers to create Innovative and breakthrough designs.

- Technology Checkpoint: The design solutions finalized in the Technology study and Design Quadrant are documented. At the highest level, this documentation will contain all the information for all the sub-component and component designs and this will act as a go to information for the future quadrants and levels. The design alternatives containing innovative and breakthrough technology, material, or process is assessed by the auditors for the company's ability to manufacture it, in terms or core capability and cost. A Go/No-Go decision is made based on the result assessment, and in case of a No-Go decision, a list of alternatives is generated and will be a deliverable at the Technology Study and Design Quadrant for the following cycle. The checkpoint auditors will be Senior Designers and Engineers.

4.4.3 Test and Validation Quadrant

In this quadrant, a standard test, planned and designed at the Technology Study, Design Alternatives, and Test Planning Quadrant, will be conducted. The test solutions will be documented and assessed at the Test Checkpoint. At higher cycles, individual components will be clubbed together to form a working sub-component or a main component, and simulated to developed test conditions. These test conditions will replicate the actual working conditions of a product in development, and also include a Factor Of Safety (FOS) standard. A detailed result is generated for analysis at the checkpoint.

- Test checkpoint: The test results generated at the Test and Validation Quadrant are analyzed and validated against the high-level functional requirements and product use conditions. A Go/No-Go decision is made based on the analysis results and a desired list of changes is generated. This list acts as additional requirement for the Technology Study and Design Quadrant at the following level, and the deliverables for this checkpoint at next level will be all the listed changes. The checkpoint auditors will be Senior Designers, Engineers and High level managers.

4.4.4 Cost and Scheduling Quadrant

The documentation made at the Technology Checkpoint at each level will act as a input to this quadrant. The cost estimation is executed using parametric modeling or other estimation methods employed by the company. At the higher levels, a bottom up estimate is constructed for a budget outline and a cost change control system is implemented as a standard to manage and navigate through the budgeting part of the project. Parametric modeling also provides a scheduling criteria for the production cycle. This helps the management to quantify the resources required to carry out the final phase of the project.

- Scheduling Checkpoint: This checkpoint is one of the critical to manage the cost and scheduling activities for the project. The auditors will analyze the cost estimate reports and compare it with the estimate reports generated in the Need Cycle. A Go/No-Go decision is made and if this report is acceptable, of then decided budgeting limits, the cost estimate is passed. If not, an alter request is passed along with a list of items where a design change is needed to cut cost. This acts as an input to the Technology Study and Design Quadrant. In higher levels, the auditors will also account for the deliverables generated in the previous levels. The checkpoint auditors will be Management, Managers, Sr. Engineers and Designers.

4.5 Manufacturing Solution Cycle

Rather than focusing on cheap manufacturing, product design (design for manufacturing) must aim to produce the low-cost platform across the life of that platform, which might include numerous re-manufacturing stages [all, 1999]. This will result in efficient manufacturing, saving money and time. Manufacturing Solution Cycle bridges the gap between design and manufacturing. The concept of Design For 'X' (Most commonly, Design for Assembly, Design for Manufacture, Design for disassembly and Design for Re-cyclability) comes into picture here. It spans a wide range of techniques applied through the physical design flow at the initial stages, and must be practiced throughout the product life cycle [Cain, 2013]. This cycle will start after a sub-component is finalized in the Design Solution Cycle; As soon as a design solution is finalized, the next logical step is to draft a drawing for manufacturability of the design solution. As sited in the literature review, different DFX tools are applicable at different stages, and as defined in the Technology Design Cycle, core capability of the company is considered in this cycle as well with respect to the ability of manufacturing.

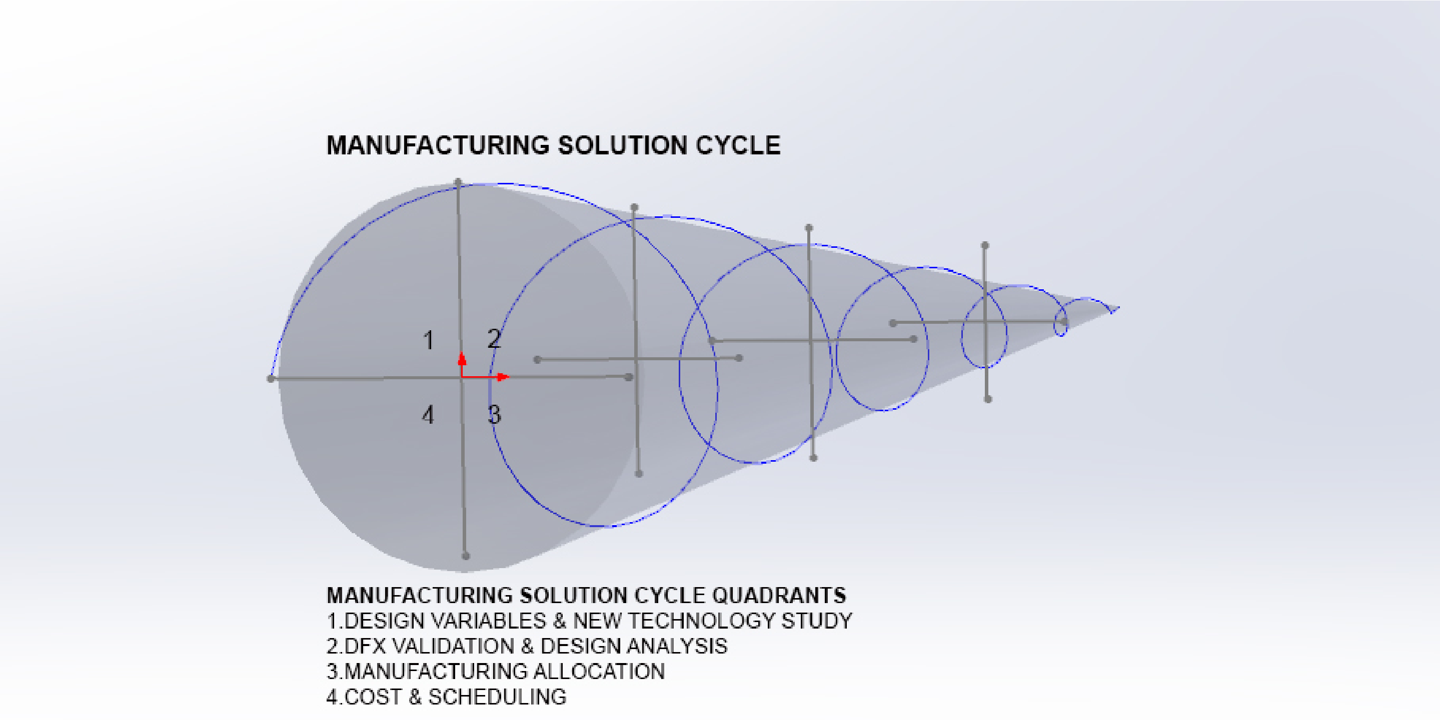

Figure 4.4: 3D Model for production cycle

4.5.1 Designing Variables and New Technology Study Quadrant

Design for manufacturing is very different from the product design carried out in the previous cycle. In this stage, the fabrication drawings are made employing GD&T, materials that will be used for each part will be selected, and the type of machining process to be employed is decided. For higher levels, this quadrant will produce assembly drawings of the components. If the design defined in the Design Solution Cycle has a specific set of requirements, a research is carried out for new/innovative manufacturing methods that will comply with the requirements. The designers should be educated about the current manufacturing capability (Core capability concept) of the company and design accordingly.

- Designing Variables Checkpoint: The checkpoint auditors will examine the drawings drafted, the machining processes,new or existing, designed for a specific component and a Go/No-Go decision is made. If the drawings are approved, they'll be sent for manufacturing (fabrication), and If the drawings or machining processes are not satisfactory, a list of required edits is generated and will be input for this quadrant in the following level. The checkpoint auditors will be senior engineers, designers, metrology experts and high level managers.

4.5.2 DFX Validation and Design Analysis

Once the methods and drawings for manufacturing are made, they are tested by either software animation or hardware prototyping. The parts should have all the functionality as specified in the previous cycle and should not hinder the functionality of other parts in conjuncture. The use of CAD/CAM software will help the designers to visualize and simulate the components, sub-components, or product depending on what level of spiral the process is in. Once that is completed, designers will analyze the design including the maximum FOS of working conditions. This will be specific to the application of the product. The Sr. Designers and Engineers working in this quadrant will analyze, brainstorm, and edit, if necessary, the drawings based on DFMA and other applicable DFX principles. This step ensures the designs are easy, economic, and produce minimum amount of waste.

- Validation Checkpoint: This checkpoint will analyze the designs obtained from the DFX validation and safety analysis and decide whether the results are acceptable and a Go/No-Go decision is made. If not acceptable, the spiral jumps back to the Designing Variables and New Technology Study Quadrant and alternative designs are developed based on the inputs received. The checkpoint auditors will be Sr.Designers, Engineers, and Management.

4.5.3 Manufacturing Allocation Quadrant

After design validation, the machining sequence is drafted depending on the types and quantities of machines available, laborers, raw materials, stocking capacity, and budget. This process will consider the manufacturing/machining time, materials, labor efficiency, and other overhead factors. Depending on the type of product, the component/sub component manufacturing rate will be decided by the Production Engineers. For example, Just In Time, Repetitive, Batch production, or Continuous production. This will make the overall manufacturing of the product more economical and the will give the management control over the production. This process will also account for machine downtime to ensure maximum utilization of all the resources available. If the products are to be outsourced, production order for that will be sent out to the outsourcing facility along with a list of requirements and design drafts.

- Allocation Checkpoint: This checkpoint will crosscheck all the proposed machining schedules and allot the same to the on-site engineers. The raw material to be ordered will be processed and a scheduled delivery time will be acquired so that the overall manufacturing process is not hampered. The checkpoint auditors will be Design engineers, On-site engineers, Lead labor and management.

4.5.4 Cost and Scheduling

The cost of manufacturing the individual part, material procurement, labor charges, overhead charges, equipment charges and time required to machine and finish the part are studied and documented. This quadrant will provide a total Manufacturing (Production/Machining) cost of the product. This is the final cost analysis and regulation stage for the Product Development Process.

- Scheduling Checkpoint: Cost and scheduling analysis reports are studied and a Go/No-Go decision is made. The developed reports are compared with Cost Budgeting generated at the Need Cycle and appropriate changes are suggested, if necessary, for the current manufacturing operations. If the auditors decide the cost analysis does not bode well with the cost budgeting, the process spirals back to the Designing Variables and New Technology Study Quadrant, where the engineers and designers will try to provide alternative solution depending on inputs from the Scheduling checkpoint. The checkpoint auditors will be Designers, Engineers, and High Level Management.

4.6 Summary

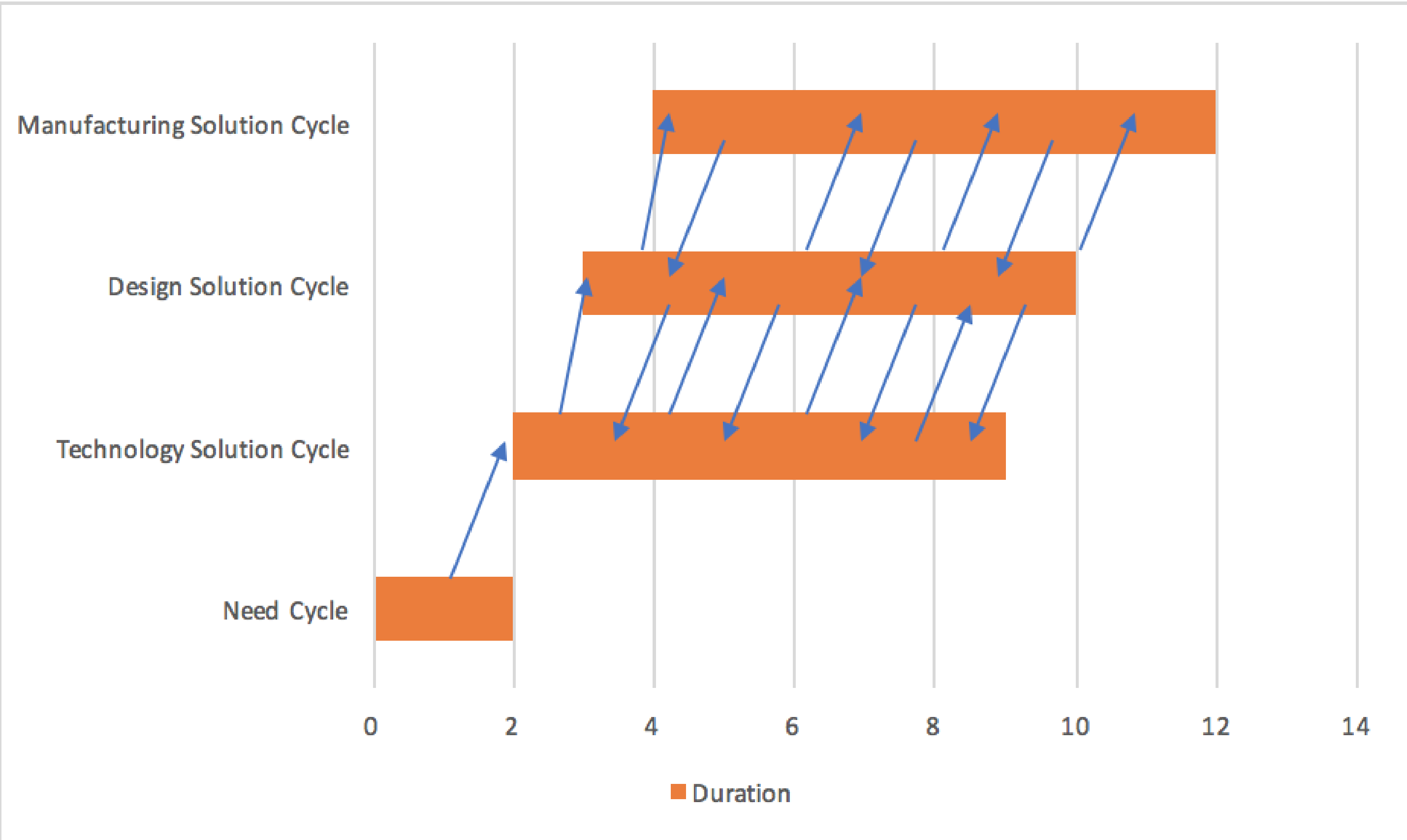

Figure 4.5: 3D Model project time line

As described in the figure, Technology Solution Cycle and Design Solution Cycle run almost parallel to each other. Once the Technology Study, Design Alternative, & Test Planning Quadrant in Technology Solution Cycle is completed, the Design Solution Cycle begins. The Manufacturing Solution Cycle begins after a sub-component is finalized in the Design Solution Cycle. This concurrent design and zigzagging allows the engineers and designers across different cycles, who are working on different sections of the project to work in close proximity and adapt to changes that may occur at any stage of the project.

Chapter 5

Research Methodology

The research followed a post positivist and pragmatism world view [Creswell, 2013], with a mixed method approach. The survey and consent form were created using an online tool - Google forms. In the introduction of the survey, a brief but comprehensive explanation of the literature review findings and the need and scope for improvement of the PD Models was described. This was followed by the 3D Hybrid Model description and survey questions. The twenty questions survey was divided into five sections, following a brief description of a section of the 3D Hybrid Model. The website, https://natarajmunoli.github.io/survey.html, contained a pre-survey briefing with introduction of the researcher, purpose of the survey, overview of the thesis, a link to the consent letter and the survey, and a thank you note at the end of the survey. The survey was administered through the link, https://natarajmunoli.github.io/survey.html, to the selected participants through email.

5.1 Participants

The eligible professionals, such as President or Vice President of Engineering, Director of Business Development, Director of Engineering, Director of Manufacturing, Managers and Sr. Engineers at a manufacturing firm that follow some form of NPD process, who would have a thorough understanding of the NPD process of their company were the target population. The informed consent letter stated that the personal information and answers of the participants will be kept confidential. For obvious reasons, it is difficult to establish a connection with a higher level executive of a firm and have them take the survey. Unless the researcher has considerable influence in his field of study. I, however, did not.

To overcome this challenge, I applied a combination of purposive (Snowball sampling) and convenience sampling to select participants. I contacted my friends and acquaintances in the U.S. and India, and requested them to deliver the link to the survey to eligible professionals. The selected sample had a definite job description in a general workforce - someone who had a firm grasp and an eagle's eye view of the New Product Development process of their company. People distributing the survey to the selected sample sizes were briefed about the applicable demographics. The survey got a response rate of 21%. It was sent to 150 people out of which 32 responded. The respondents represent an array of sectors in the manufacturing industry. Though the number of respondents is small, they represent issues that are faced in their own sector, and this adds to the validity of the results.

5.2 Data Analysis

The survey was administered through a survey module of Google forms. A total of 32 people responded. The survey had 2 introductory questions and 17 questions with 5-point Likert scale option and were analyzed using the quantitative methods of data analysis. The options that respondents chose for each question was represented by a pie-chart, divided according to the percentage of selection for each question. The 5 point Likert scale employed had options, 1. Very likely 2. Likely 3. Does not apply/Does not make a difference 4. Unlikely 5. Very unlikely. Figure 6.1 shows an example of the data collected and is represented through a pie-chart. This division clearly shows whether the 3D Hybrid Model had a positive or negative impact on (add). A descriptive statistic can be inferred from the pie-chart. The combined percent of options 1 & 2 represents the respondent's belief - 3D Hybrid Model has an advantage over the currently followed method at a particular stage. This is a confirmation that all or some of the issues present would be solved by following the steps employed by 3D Hybrid Model at that stage. Similarly, the combined percentage of options 2, 3 & 4 represent the respondent's belief - 3D Hybrid Model has no distinctive effect or the currently followed method addresses the persisting issues better. This method was used to analyze each question, and as explained in the Discussion section, each question addresses a particular issue faced at multiple stages during product development.

The 20th question is descriptive. Respondents commented their thoughts, suggestion and criticisms. These comments provided valuable insights into their company's method and approaches towards the issues in question. These comments provide a platform for the next iteration of 3D Hybrid Model.

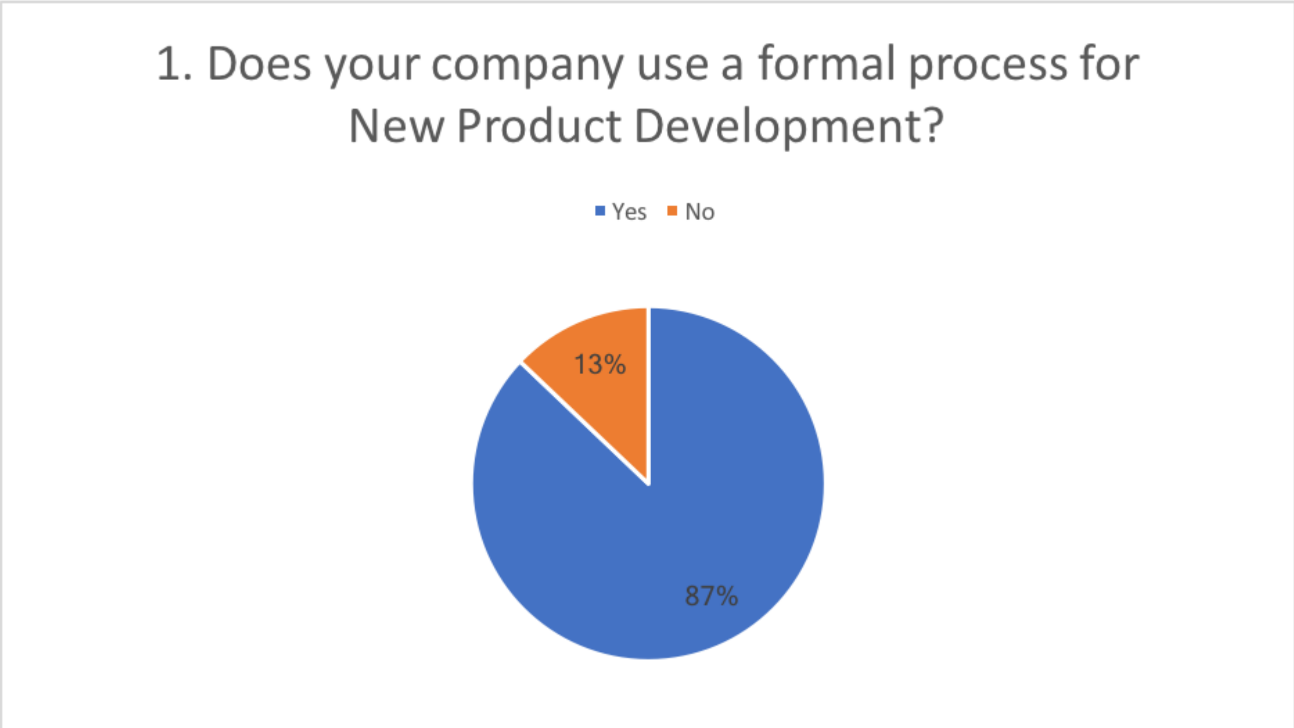

Figure 5.1: Example of Q1 response Pie Chart

Chapter 6

Results

As explained in the Data Analysis section, Google Forms provides a comprehensive report of the respondents' answers. Below is the detailed analysis of each question.

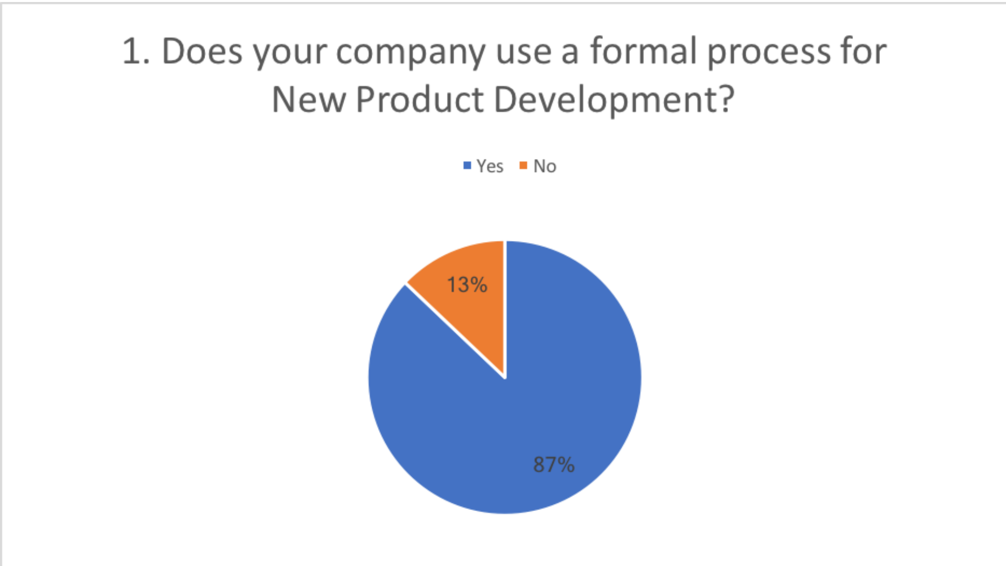

Figure 6.1: Q1 response Pie Chart

87% of the respondents' companies follow some sort of New Product Development process. This suggests that despite partially or strictly following a New Product Development process that fits their company's structure, they all constantly face some hindrance or shortcoming that cannot be dealt with the currently followed NPD process, and that negatively impacts the project. Though 13% of the respondents' said their companies do not follow any form of NPD process, they face various roadblocks and they need to have a counter solution to every problem. The solution adopted by these companies may not be described in the main-stream NPD Processes but may describe an alteration, subset, or an altered custom solution to solve the company's specific issue. If the company fails to incorporate any solution, no matter how minuscule, overtime, it will pose a pernicious threat.

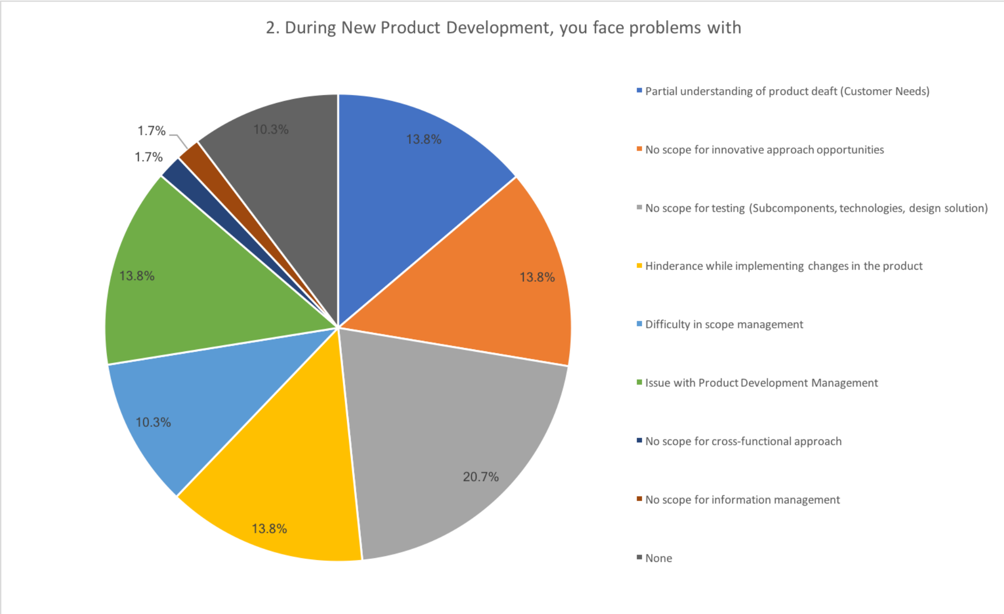

Figure 6.2: Q2 response Pie Chart

My literature review for this thesis reviewed three current NPD processes to conclude that the current NPD models address some important issues either partially or not at all; as shown in Figure 7.3, a single model in itself cannot provide a solution to the issues faced as a result of bottlenecks or shortcomings of the Product Development Process [Sharafi et al., 2010].

The respondents' answers align with my findings. The following are the top five areas where the respondents experienced the shortcomings in their company's PD Process.

- No scope for testing (Subcomponents, Technologies, Design Solution) - 20.7%
- Hindrances with implementing changes in the product - 13.8%
- No scope for innovative approach opportunities - 13.8%
- Issues with product development management - 13.8%
- Partial understanding of product draft (Customer Requirements) - 13.8%

	Product Concept		Product Design		Production Design		Simultaneous Development	Product Development Management	Information Management	Iterative Approach	Cross Functional Approach
	Requirements	Product Draft	Engineering	Testing	Process Design	Organization & Supply					
Stage-gate	●	○	**O**	**O**	○	○	○	●	○	○	**O**
Spiral Model	●	●	●	●	●	○	○	**O**	○	●	**O**
Axiomatic Design	●	●	●	**O**	**O**	○	**O**	○	○	●	**O**

● Fully addressed **O**Partially addressed ○Not addressed

Figure 6.3: PD Models Compare

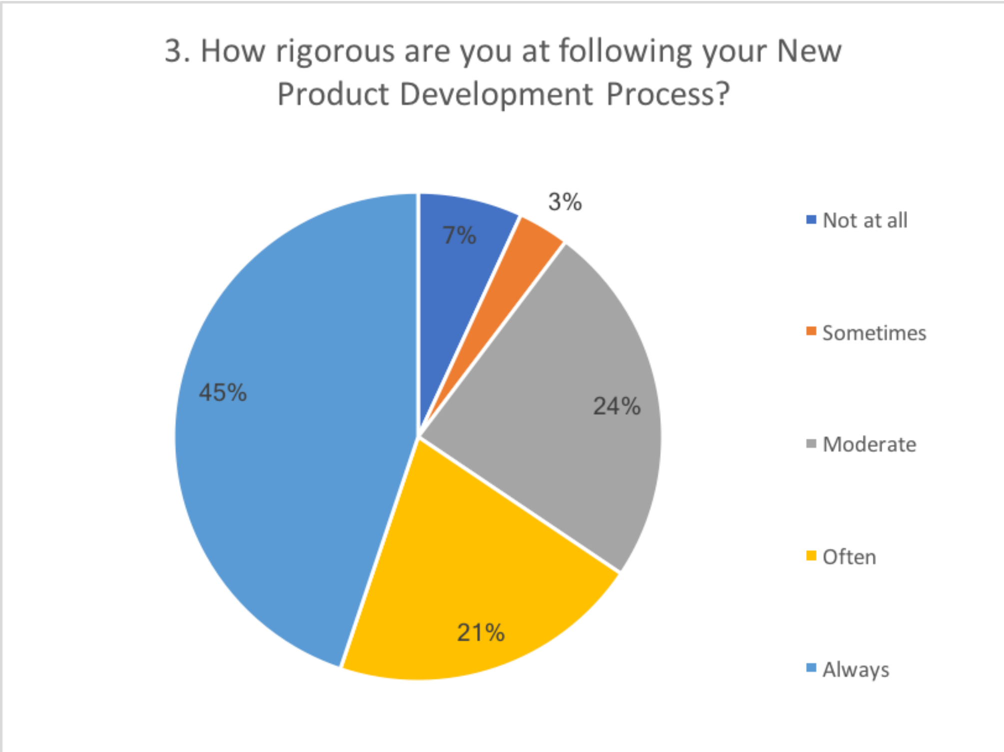

Figure 6.4: Q3 response Pie Chart

Of the 87% participating companies, 93% of the respondents said that they follow some sort of NPD Model on some occasions. According to [Cooper and Kleinschmidt, 2007], "the strongest driver of profitability is the existence of a high-quality, rigorous new product process-one that emphasizes up-front homework, tough Go/Kill decision points, sharp early product definition, and flexibility. By contrast, merely having a formal new product process has no impact at all on performance!". Companies that followed strict and well defined New Product Development processes performed better than the ones that did not. Hence, ideally, the company's response leans towards incorporating some form of NPD Process.

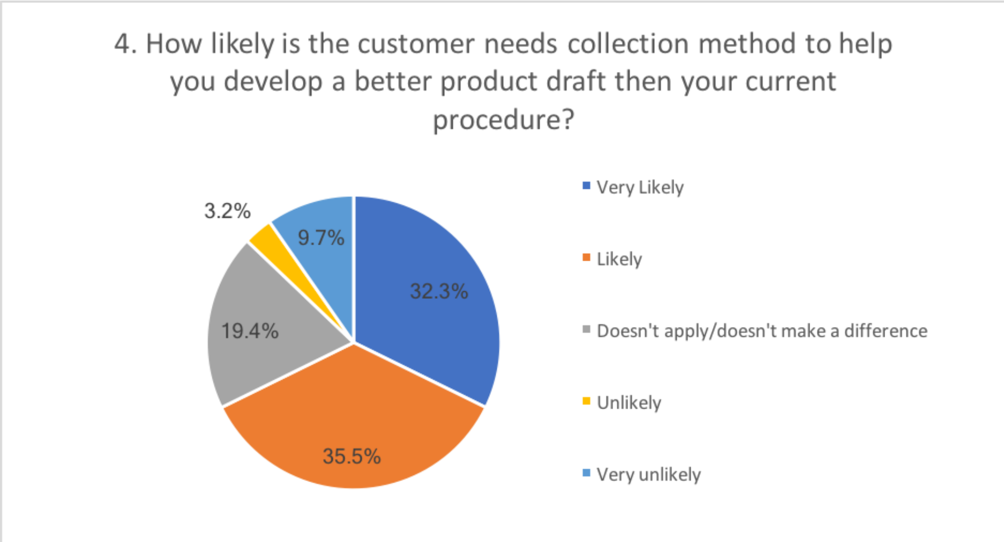

Figure 6.5: Q4 response Pie Chart

67.8% of the respondents said that, Customer Needs Collection method of the 3D Hybrid Model positively influences the Customer Needs Collection process over the current NPD Model followed at their company.

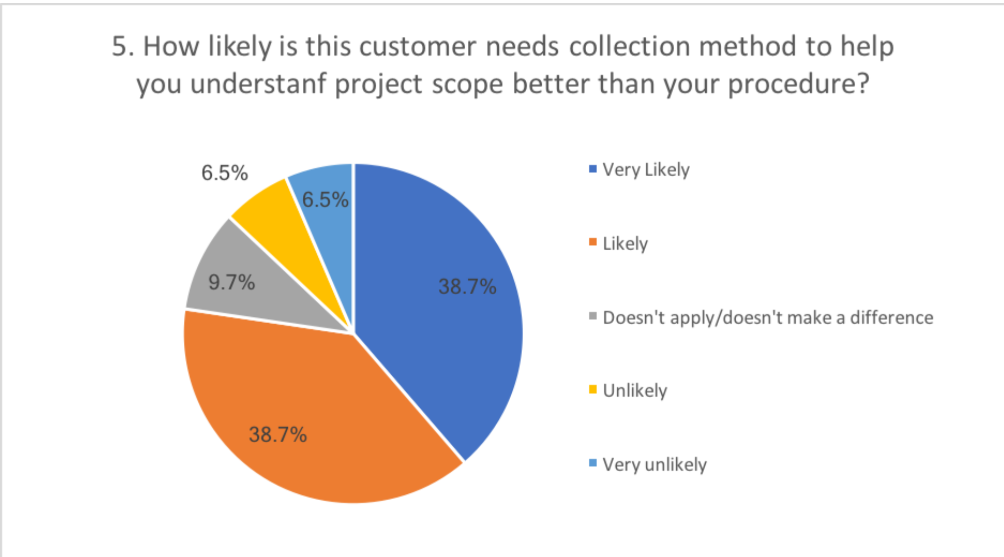

Figure 6.6: Q5 response Pie Chart

77.4% of the respondents said that, Customer Needs Collection method of the 3D Hybrid Model positively influences the understanding of project scope than the current NPD Model followed at their company.

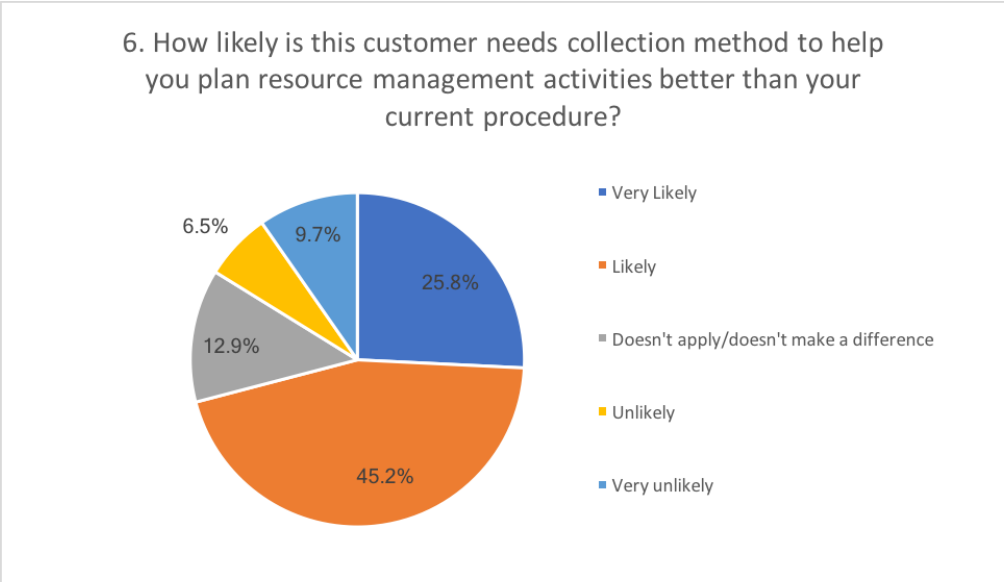

Figure 6.7: Q5 response Pie Chart

71% of the respondents said that, Customer Needs Collection method of the 3D Hybrid Model positively influences resource management planning activities over the current NPD Model followed at their company.

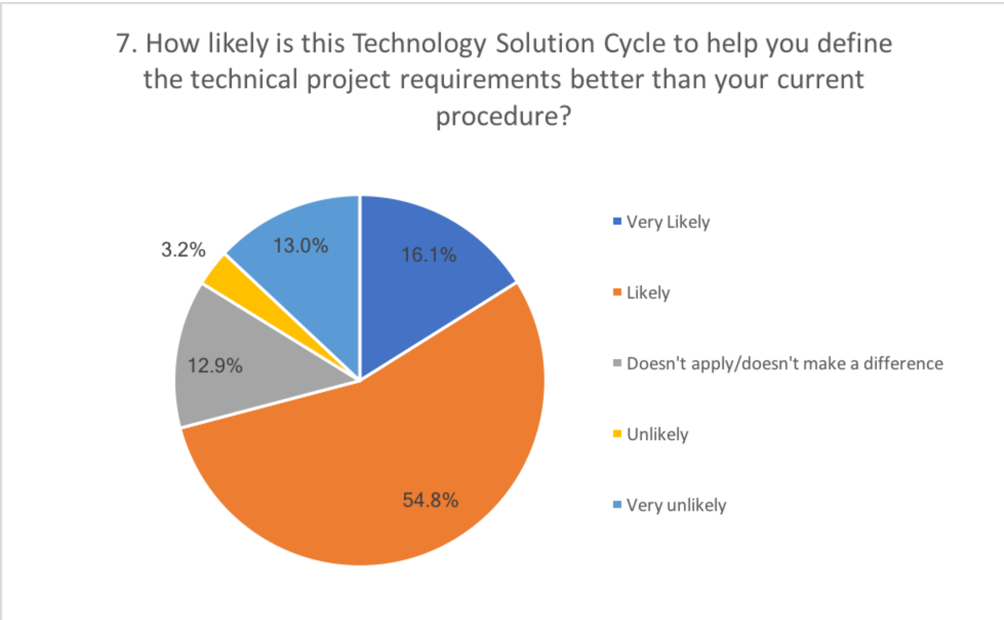

Figure 6.8: Q7 response Pie Chart

70.9% of the respondents said that, Technology Solution Cycle of the 3D Hybrid Model positively influences technical project definition requirements over the current NPD Model followed at their company

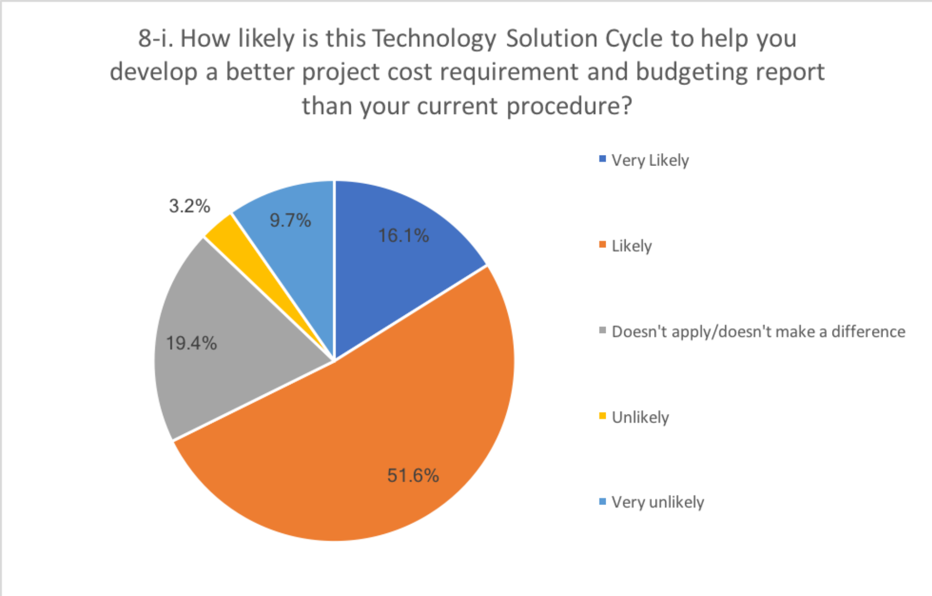

Figure 6.9: Q8-i response Pie Chart

67.7% of the respondents said that, Technology Solution Cycle of the 3D Hybrid Model positively influences development of project cost requirements and budgeting reports over the current NPD Model followed at their company.

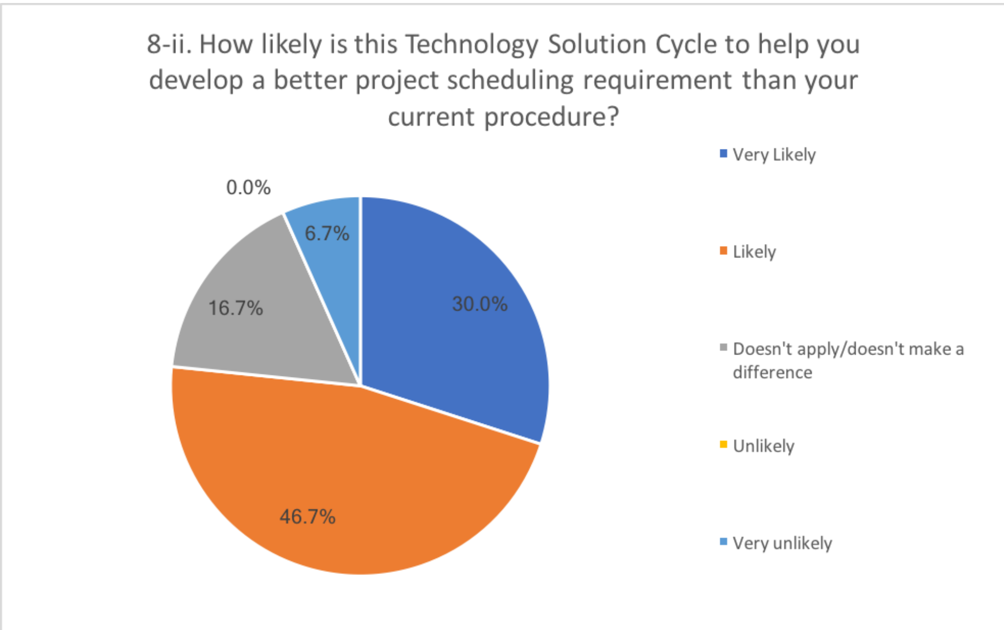

Figure 6.10: Q8-ii response Pie Chart

76.7% of the respondents said that, Technology Solution Cycle of the 3D Hybrid Model positively influences development of project scheduling requirement over the current NPD Model followed at their company.

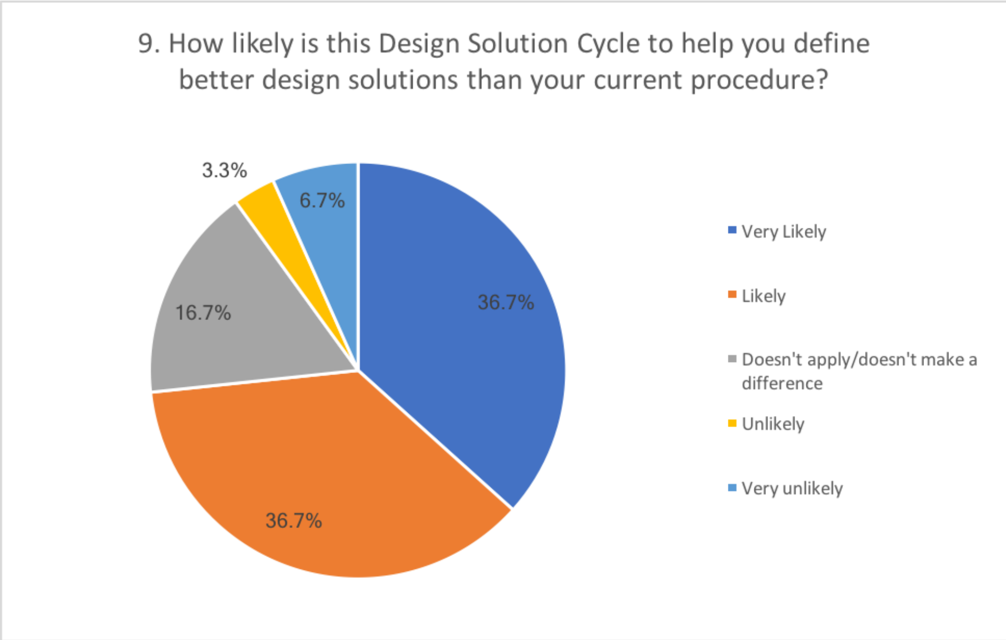

Figure 6.11: Q9 response Pie Chart

73.4% of the respondents said that, Design Solution Cycle of the 3D Hybrid Model positively influences defining design solutions over the current NPD Model followed at their company.

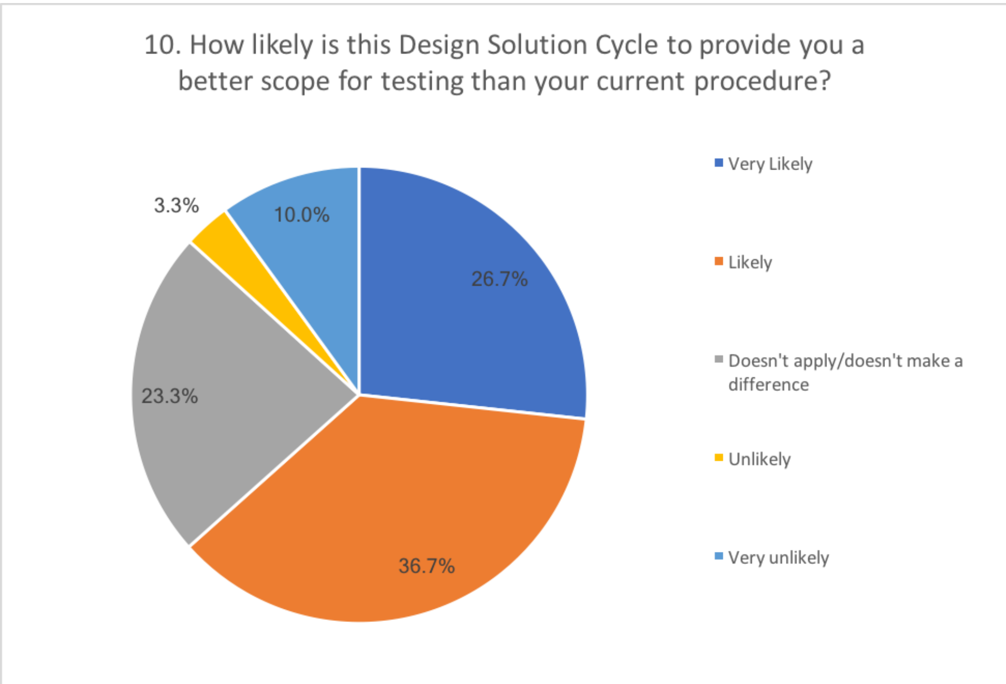

Figure 6.12: Q10 response Pie Chart

63.4% of the respondents said that, Design Solution Cycle of the 3D Hybrid Model provides positive scope for testing over the current NPD Model followed at their company.

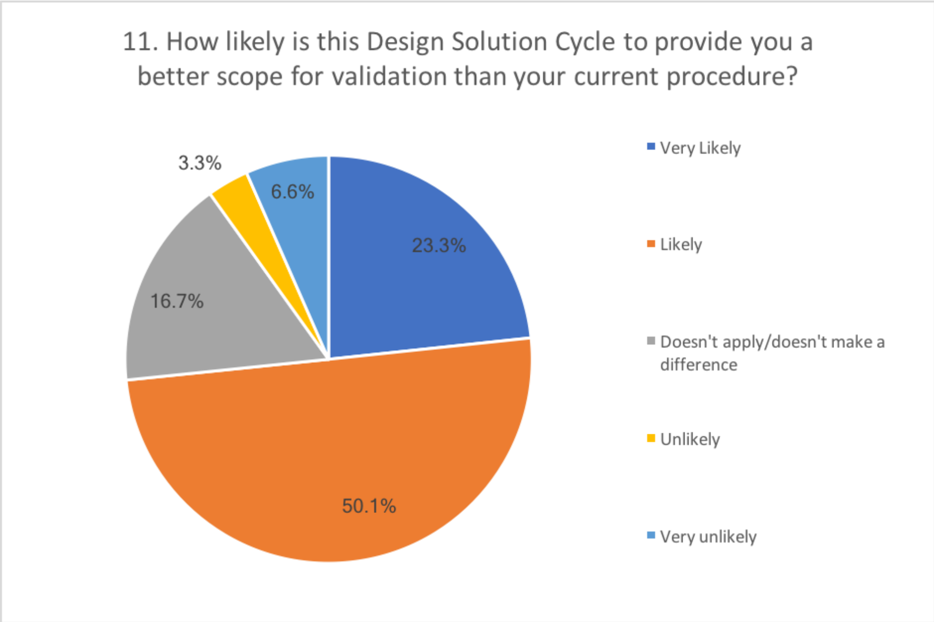

Figure 6.13: Q11 response Pie Chart

73.3% of the respondents said that, Design Solution Cycle of the 3D Hybrid Model provides positive scope for validation over the current NPD Model followed at their company.

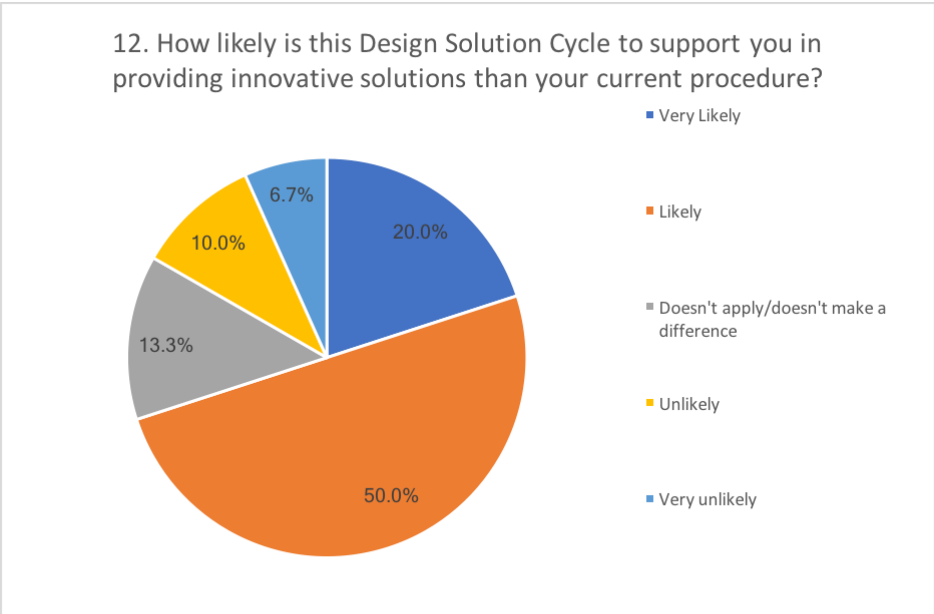

Figure 6.14: Q12 response Pie Chart

70% of the respondents said that, Design Solution Cycle of the 3D Hybrid Model positively influences in providing innovative solutions for requirements over the current NPD Model followed at their company..

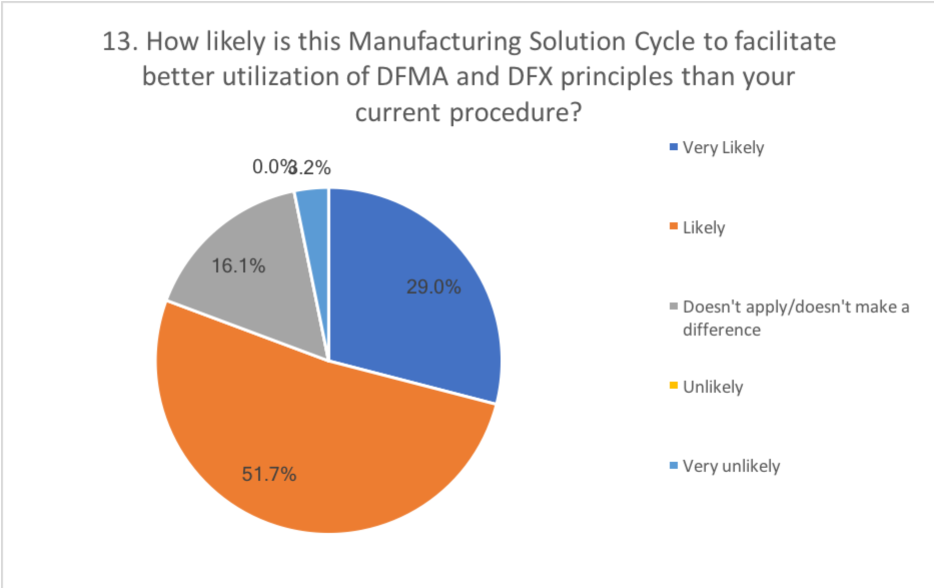

Figure 6.15: Q13 response Pie Chart

80.6% of the respondents said that, Manufacturing Solution Cycle of the 3D Hybrid Model positively influences utilization of DFMA and DFX principles over the current NPD Model followed at their company.

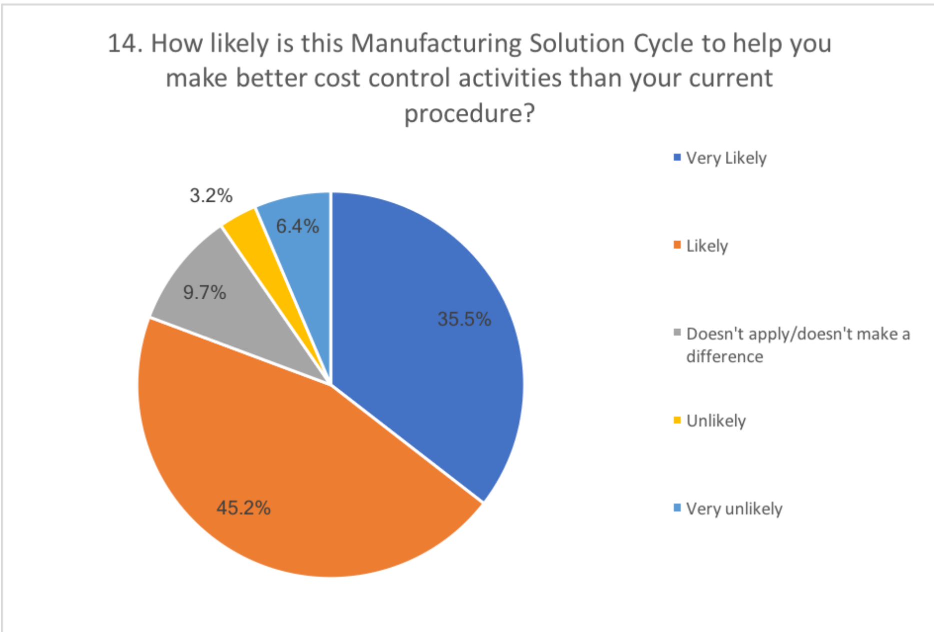

Figure 6.16: Q14 response Pie Chart

80.7% of the respondents said that, Manufacturing Solution Cycle of the 3D Hybrid Model positively influences cost control activities over the current NPD Model followed at their company.

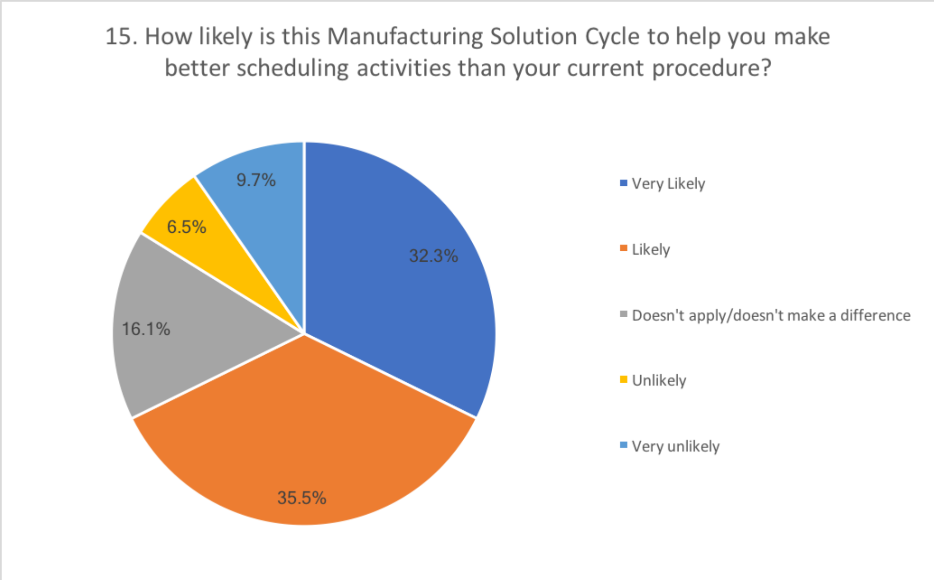

Figure 6.17: Q15 response Pie Chart

67.8% of the respondents said that, Manufacturing Solution Cycle of the 3D Hybrid Model positively influences scheduling activities over the current NPD Model followed at their company.

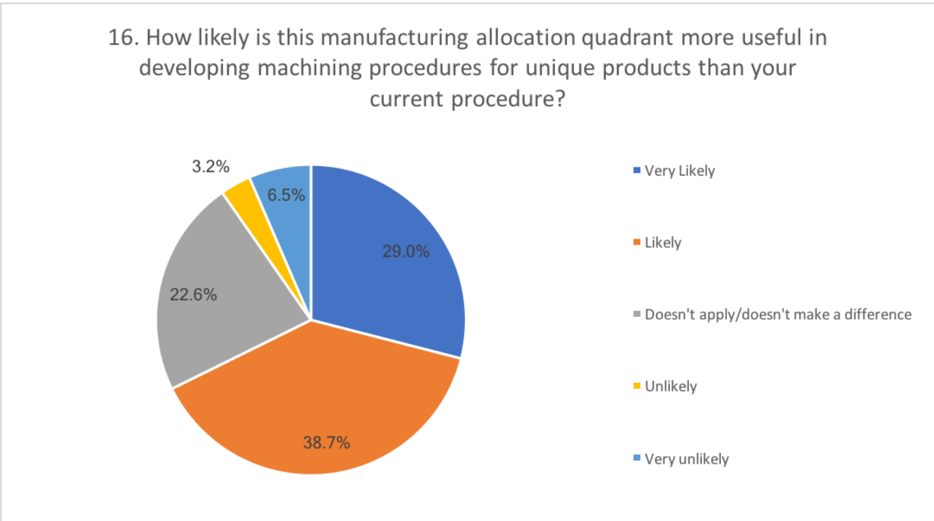

Figure 6.18: Q16 response Pie Chart

67.7% of the respondents said that, Manufacturing Allocation Quadrant of the 3D Hybrid Model positively influences developing machining procedures for unique products over the current NPD Model followed at their company..

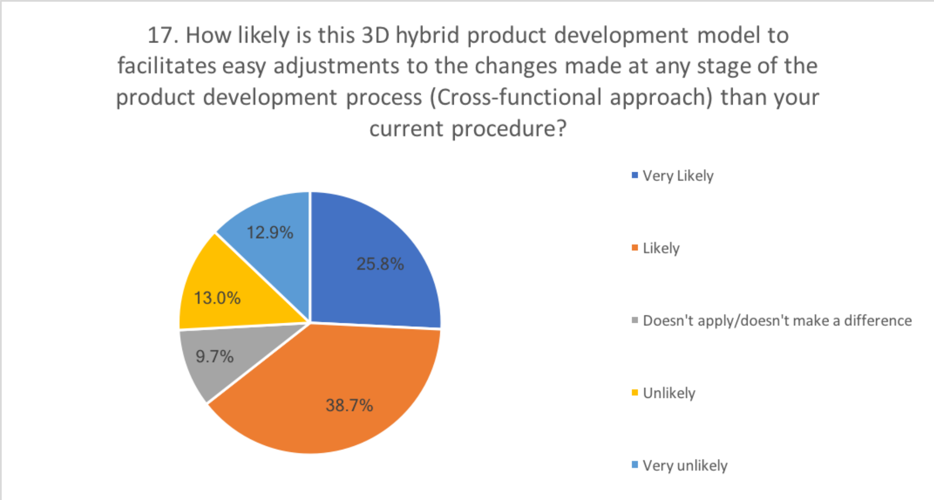

Figure 6.19: Q17 response Pie Chart

64.5% of the respondents said that, 3D Hybrid Model positively influences facilitation of easy adjustments to the changes made at any stage of the PD Process over the current NPD Model followed at their company.

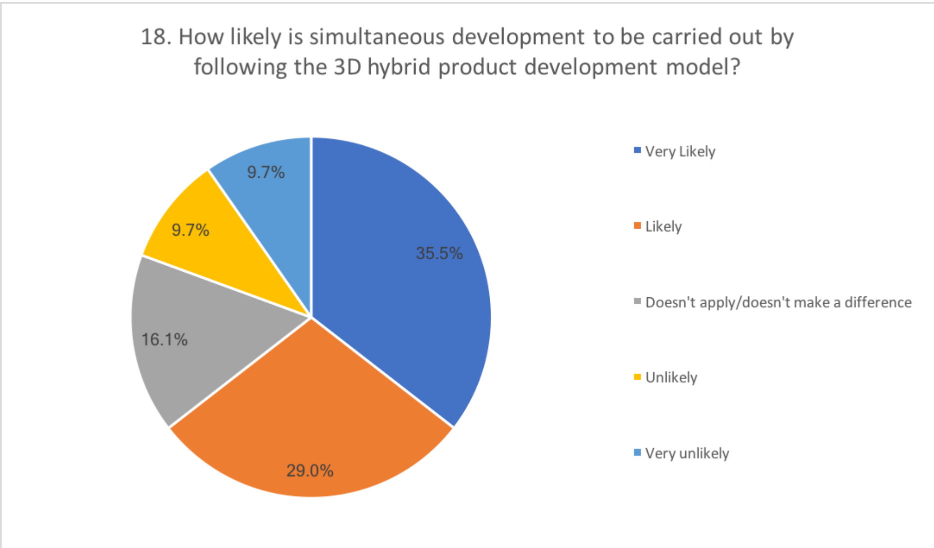

Figure 6.20: Q18 response Pie Chart

64.5% of the respondents said that, 3D Hybrid Model positively influences simultaneous development over the current NPD Model followed at their company.

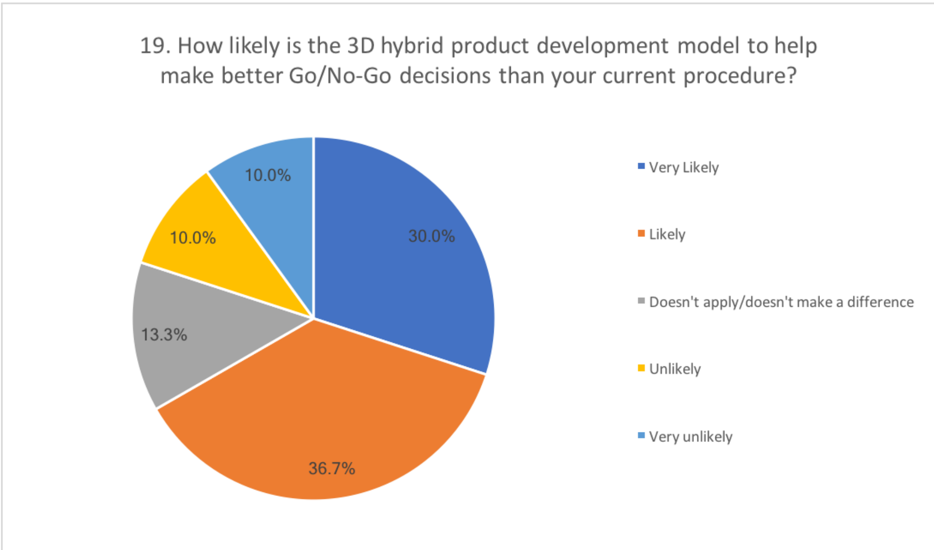

Figure 6.21: Q19 response Pie Chart

66.7% of the respondents said that, 3D Hybrid Model positively influenced them to make better GO/NO-GO decisions over the current NPD Model followed at their company.

To learn about any ambiguity, concerns, suggestions, or critique, the last question of the survey was a descriptive question, and the respondents have provided divergent comments and suggestions that complement, criticize, and provide insights about 3D Hybrid Model from their perspective. All the comments by the respondents are listed below. Based on these comments, possible iterations for the 3D Hybrid Model can be extracted as a future scope.

- Depends heavily on the volatility of the product. Not necessarily one solution fits all the problems. 3D model can give out different ways to develop a product but at the end depends largely on the customer base and the industry you are dealing with.

- This is Great!

- These formal structured procedures are for people with no or little experience and self discipline. Those of us who have been doing product development for 40 years don't need such procedures. Do you need a step-by-step process for tying your shoe laces when you have been doing it semi-automatically for many years?

- Execution is the key.

- Seems like a good idea

- My suggestions are 1. Design Review is essential at various stages. 2. Verification stage is needed to check whether out put met the Input requirements. 3. Field test before release need to be addressed. 4. Final approval is needed from expert other than who made the design.

- Product Development / Program Management is Key for any industry in the current changing speed . This will help to align Design - Development & Manufacturing - Supply chain functions aligned to customer expectations

- This has to improve a lot to be feasible on a real product. I went through the different cycle it does capture everything theoretically. In the real world time and money are two key factors which drive the cycle I would suggest taking a product and going along with your cycle.you can show how it works much better. Now its very theoretical. Do more case studies All the best

- Apart from the customer requirements, suggestions from the manufacturing persons can be a good input. The past failure data can be a good inputs. Competitor's performance data can be a input. Design reviews and cost review at regular intervals will help and give some inputs.managing the time need to be considered. The life cycle cost of the product need to be considered.

- 3D will help to avoid errors
- TO TEST THE SYSTEM PERFORMANCE FOR WHICH THE PRODUCT IS DESIGNED.
- Primarily Design Review (PDR). Design Reviews (DR's) and Critical Design Review (CDR) are terms which I use during the design process, I didn't see this terms in your work. these are very useful meetings which put the development process in a strict time frame. 4.2.1 I would add to survey and personal interview the following: industrial reports, questionnaire, marketing research, common practice and industrial standards and regulations. You must be aware of 'personal interview' as people tend to push their agenda, which sometimes is totally opposite to the industry requirement. You must rely on objective information like independent research etc. 4.2.3 Cost and scheduling quadrant is very subjective, engineers will cut the cost down to keep their "baby" alive, CEO/CFO will use this tool to kill it. I wouldn't put this Go/Kill condition at this early stage. instead I would put as a goal the market price for the product, rather than speaking about product cost, which is irrelevant at such early point of the project.

General statements I believe that ideas for product must come from Marketing and Sales, I have seeing brilliant products sprung from engineering without success, due to lack of commitment from sales. Add a general condition to the entire process, every time there is a major impact on the product cost / profit the CEO/CFO/ Marketing manager must be in the loop and approve it. I enjoyed reading your work. Good Luck !

Chapter 7

Discussion

The qualitative and quantitative data collected for quadrants of each cycle clearly suggests that all the processes and methods employed in the quadrants to tackle the issues identified in the literature review, work. According to the respondents, the processes and concepts employed in the 3D Hybrid model help them tackle the existing issues in one or more areas during product development process and that's why all questions got a response rate of 60% and above for the combination of 1st & 2nd options (Very likely and likely). The quantitative data only compares the identified problematic target areas with the 3D Model, it does not determine the resulting impact of employing the 3D Hybrid Model. We do not know the current practiced method at the respondent's company that was causing issues in the process, and the corrective measures undertaken.

Analyzing the respondent's response to the 20th question, we learn that each company has its own unique roadblocks/issues. The respondents tried to analyze how well or how poorly the 3D Hybrid Model solved that and gave suggestions about what might be able to solve the issues. These suggestions, individually, will direct further researchers towards "new features" the next iteration of 3D Hybrid Model may possibly accommodate.

A learning point from the survey is that, despite being functional and creating new products constantly, there are some major issues that companies face during the PD Process. Although these issues do not stop the company from delivering new products, they surely add on to the cost, time and other valuable resources. These issues are the result of not having a PD model that addresses all aspects of the development process, is not agile, does not promote inter-department communication. This is in accordance with all the studies referenced in the literature review section of this thesis. Responses to Question 20 of the survey revealed specific area/s where there are limitations and issues, their nature, severity and the resulting effects of these issues. For example: One of the comment from the respondent was that, there is a need of final approval on a design from an expert/lead engineer. The Spiral Model is designed such that at the end of each spiral(level), the checkpoint inspector (who will usually be a senior engineer or a manager) has to approve the designs and only then the process will move forward, else sent back for alterations.

One of the main concern the respondents have is the actual feasibility of the model, most of them agree that theoretically it does solve some issues that are caused by their PD Process shortcomings. From the researcher's point of view, testing the model on an actual product in development will be the next step to prove its competency.

One responder thought that the PD Process depends on the volatility of the product and there might not be a one size fits all model. This issue cannot be accurately answered just by analyzing the survey results. The 3D Hybrid Model should have to be implemented in different domains of the manufacturing industry and for development of variety of products, and only then it can be determined whether the 3D Model is flexible enough.

Chapter 8

Limitations

Qualitative data only confirms whether the 3D Hybrid Model is better or not. It does not comprehensively compare the participating company's NPD model with the 3D Hybrid Model because of the following reasons.

1. The survey only contains specific questions that compare a specific aspect of the NPD process where the shortcomings were found during the literature review.

2. I, as a researcher, had no access to the participating respondent company's NPD structure.

3. The respondents will not reply to survey if it is very long or time consuming, [Deutskens et al., 2004] and has no personal or professional benefits to the respondents.

4. Respondents, too, did not have access to the detailed description of the 3D Hybrid Model.

Chapter 9

Conclusion and Future Scope

This thesis attempted to provide a new, New Product Development model that acknowledges the relevance of incorporating different Product Development structures for different stages of Product Development by extracting its ideas from three significant NPD models - Stage-Gate Model, Spiral Model and Axiomatic Design. The qualitative data analysis suggests the 3D Hybrid Model solves issues of the inept New Product Development process of the respondents' companies. However, it does not eliminate all the shortcomings and issues faced by their current NPD process; to expect this from the theoretical 3D Hybrid Model is also not realistic. Due to the limitation of time, resources and opportunity, survey was the best possible way to prove that the 3D Hybrid Model had potential to eliminate some issues caused by PD Process bottlenecks. The qualitative data collected from the survey suggests that, the 3D Hybrid Model does address some important issues that the industries currently face. The quantitative data collected reflects further on the positive points and possible limitations of the 3D Hybrid Model.

The best point to initiate further research is by considering the respondent's comments and modifying the 3d Hybrid Model. I hope that my research and results acquired will motivate researchers to further iterate this NPD Model and test it by implementing it in the an industrial setup or develop a product using the iterated model.

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