AN ENHANCED NEW PRODUCT DEVELOPMENT (NPD) MODEL AND THE APPLICATION OF TAGUCHI METHODS IN UPSTREAM NPD ACTIVITIES

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An Enhanced New Product Development (NPD) Model and the application of Taguchi methods in upstream NPD activities

BY

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To my loving family

Abstract

New product development (NPD) has emerged as a key aspect in today's manufacturing industry which is constantly being driven by global competition, advancing technologies and the need for frequent introductions of newer, better quality and lower cost new products. Having an efficient and a well-structured NPD process is critical to the success of a manufacturing organization and has led to research on reengineering and continuously improving the NPD process.

This thesis proposes a NPD process model, viz., the NPRP (New product realization process) model, aimed at developing high quality products at low cost and at an accelerated rate. The NPRP model is a comprehensive model (constituting five concurrent phases), which encompasses all NPD activities in a manufacturing organization, right from the conception of the new product idea to the commercialization of the product in the market. The model provides a detailed structural framework for the NPD process and elaborates the constituent activities, milestones, deliverables and tools involved. The model places major emphasis on the upstream activities of the NPD process, viz., Opportunity evaluation and Product and Process design; as they are crucial in affecting the quality, cost and development time of a new product. The NPRP model proposes Taguchi method (TM) as a quality-engineering tool for improving the quality and pace of product concept design activities, which form a crucial part of the front-end

NPD activities. TM is proposed as a tool for realizing high quality/low cost product with shorter development cycles.

The thesis further successfully demonstrates the potential of TM as a front-end NPRP tool through a case study in LOM process optimization. LOM or Laminated Object Manufacturing is a rapid prototyping process used for manufacturing concept prototypes of new products in the manufacturing industry. The thesis furnishes details of the case study and presents results illustrating improved LOM process quality and reduced process time; eventually contributing to high quality/low cost and faster NPD.

The NPRP model can serve as an initial framework/guideline for establishing and implementing a systematic NPD process in a manufacturing organization and the LOM process optimization case study using TM furnishes new avenues for further quality improvement and problem solving in LOM, both for industrial and educational purposes.

Acknowledgements

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A	Heater speed
A_1	Sum of all S/N values at level 1 of factor A
A_2	Sum of all S/N values at level 2 of factor A
AxB	Interaction between factors A and B
a	Number of levels of factor A
B	Heater temperature
b	Number of levels of factor B
C	Cutting speed
D	Laser power
E	Cross hatch size
e	Experimental error
F	F-ratio
f	Number of factors in an experiment
k	Quality loss coefficient
L_4	Orthogonal array with 4 experimental trials
L_8	Orthogonal array with 8 experimental trials
L_9	Orthogonal array with 9 experimental trials
L_{16}	Orthogonal array with 16 experimental trials
L_{27}	Orthogonal array with 27 experimental trials

L_{64}	Orthogonal array with 64 experimental trials
L(y)	Quality loss function
l	Number of levels of a factor
m	Target value of the quality characteristic
MS	Mean square
MSE	Mean square error
μ	Mean
n	Total number of observations of the quality characteristic in an experiment
N	Total number of S/N values in an experiment
ν	Degrees of freedom
ν_A	Degrees of freedom associated with factor A
ν_B	Degrees of freedom associated with factor B
ν_{AxB}	Degrees of freedom associated with the interaction AxB
ν_C	Degrees of freedom associated with factor A
ν_D	Degrees of freedom associated with factor A
ν_E	Degrees of freedom associated with factor A
ν_T	Total degrees of freedom
ν_x	Degrees of freedom associated with factor X
P	Percent contribution
S/N	Signal to noise ratio
SS	Sum of Squares

SS_A	Sum of squares for the factor A
SS_T	Total Sum of squares
SS_e	Error sum of squares
Σ	Sum of entities
σ^2	Standard deviation
y	Actual value of the quality characteristic on the QLF curve
y_i	$_{ith}$ value of the quality characteristic in an experimental trial

List of Abbreviations

ANOVA	Analysis of variance
BMP	Ballistic particle manufacturing
CE	Concurrent engineering
CAD	Computer aided design
CAE	Computer aided engineering
DOF	Degrees of freedom
DFA	Design for assembly
DFM	Design for manufacture
DSP	Direct shell production casting
FDM	Fused deposition modeling
FFE	Fractional factorial experiment
LOM	Laminated object manufacturing
LSL	Lower specification limit
MTC	Manufacturing Technology Centre
MUN	Memorial University of Newfoundland
NPD	New Product Development
OA	Orthogonal array
RP	Rapid prototyping
R & D	Research and development

SLA	Stereolithography apparatus
SLS	Selective laser sintering
SGC	Solid ground curing
STL	Stereolithography
TM	Taguchi Method
USL	Upper specification limit
3DP	Three dimensional printing

Chapter 1

1. Introduction

In today's rapidly evolving technological environment and increasing global competition, New Product Development (NPD) has gained major emphasis in the manufacturing industry [15, 23, 24, 44].

In simplest of terms, NPD is the phenomenon of developing newer, more innovative products. The ability to introduce new products faster, more frequently and of higher quality has become a distinct competitive advantage. Continuing Japanese success in the international market, in manufactured goods ranging from automobiles to electronic products, has been attributed to their ability to introduce a constant stream of low-priced, high quality new products at a frequent pace.

In all industrial segments worldwide, the industries which have been able to innovate successfully have become market leaders. Firms like Sony, Toyota, Motorola, Intel, Microsoft, 3M, Merck, Canon are a few examples of such successful innovators. Research shows that product innovation drives business growth [21] and almost 50% of the revenue of successful leading firms is attributed to their new product introductions [24].

In the face of fierce international competition, prudence lies in continuing to devise new ways in order to remain competitive. Product innovation has been cited as a critical factor for a company to keep ahead and thereby survive. The ability of firms to bring newer, cheaper products to market in shorter intervals has accounted for larger market shares in the recent past and will continue doing so in the 21^{st} century.

The ability to successfully innovate depends upon successful NPD practices [24]. These practices include a formal NPD process and other tools that help develop products which emerge as market winners. The winning new products are essentially characterized by high quality, low cost, short development cycles and high perceived customer value.

The scope of this thesis is concerned with the development of such successful new products by concentrating on two aspects of NPD practices. The first aspect focuses on developing an efficient NPD process model which provides an effective process to accomplish the overall development of high quality new products in a cost effective and accelerated manner. In order to design such high-quality/low-cost new products, the second aspect explores Taguchi's robust design method as a front-end NPD process tool for building quality in new products by concentrating on the product design stage. A case study in industrial Rapid Prototyping (RP), featuring Laminated Object Manufacturing (LOM), is presented to demonstrate the potential of applying Taguchi method as a NPD tool.

1.1. Organization of the thesis

Chapter 1 briefly introduces the concept of NPD in the manufacturing industry and provides an introduction to the scope and the organization of the thesis.

Chapter 2 gives an overview of the phenomenon of new product development in the manufacturing industry. It explains the concept of NPD, elaborates on basic terminology, issues and relevant research in new product development.

Chapter 3 comprises a theoretical NPD process model, called the NPRP (New product realization process) model, developed towards realizing a more efficient and effective NPD process for the development of high quality/low cost new products with accelerated development times. The NPRP model advocates the use of Taguchi Method (TM) as a front-end process tool for the realization of high quality/low cost accelerated NPD

Chapter 4 gives an overview of Taguchi Method (also known as Robust design methodology) and introduces the scope of its application in design of new products for achieving high quality at low cost. An explanation of the elements of Taguchi Methods like Taguchi's quality philosophy, quality loss function, steps of robust design, S/N ratio and orthogonal arrays is included.

Chapter 5 presents a case study featuring LOM (Laminated Object Manufacturing) process optimization using Taguchi method. LOM is a rapid prototyping process used to create physical models of product concepts in the initial stages of the NPD process. The study is conducted to demonstrate the application of TM as a potential front-end NPRP tool for improving the quality of the LOM process. The chapter furnishes details of the case study and presents results illustrating improved LOM process quality and reduced process time, which eventually contributes to high quality/low cost and faster new product development; thus demonstrating the TM as an effective NPRP tool.

Chapter 6 presents the overall conclusions of the research and recommendations for further work.

Chapter 2

2. Background Review of New Product Development

New Product Development is concerned with the development of new products and encompasses a wide variety of aspects in product development, right from conception to the launch stage. Since NPD is a multi-faceted complex phenomenon involving a broad range of topics, the intent of this review is to briefly apprise the reader with the basic concepts and elements comprising NPD.

The chapter is organized around the following main topics:

- New Product Development in the Manufacturing Industry - a brief overview
- Product Innovation and Type of New Products
- NPD Process
- Organizational Structure
- Tools and Techniques

2.1 New Product Development in the Manufacturing Industry - a brief overview

2.1.1 Recent trends in the Manufacturing industry

NPD is concerned with the creation of new products. It encompasses all aspects involved in developing new products right from conception to product launch.

In the past two decades, the manufacturing industry has seen many upheavals. Manufacturing philosophy has undergone a substantial change. Cost-reduction, quality management, innovation, downsizing and lean production have become basic tenets in the field of manufacturing. Competition has moved from competing on cost and quality in the 80s to shorter time-to-market, product innovation and mass-customization in the 90s. Low cost and high quality being the universally accepted pre-requisites for business, the present emphasis is on product innovation and time-to-market. The ability to develop innovative, quality products in shorter cycle times is the driving factor for a manufacturing organization's success at present.

The Japanese firms have enjoyed phenomenal success in the international market owing to their high quality innovative products. European and North American firms have undergone major restructuring, reorganization and re-engineering in order to attain parity in product cost, quality and productivity with their Japanese counterparts.

Product innovation has emerged as a significant factor critical for survival and success in the international marketplace. It has become evident that new products are fundamental for both the viability and continuous growth of a company [23]. According to a 1997 survey, major market leaders attributed 50% of their total sales revenue to new products introduced in the past five years [24]. New products are the single largest predictors of investment in the industry these days and most companies are counting heavily on new products for profitability and growth. Discovery of new products and processes and diffusion of these innovations will continue to be the key element in the long run as well [51].

2.1.2 Factors driving NPD in the Manufacturing Industry

The factors driving NPD in the manufacturing industry can be summed up as follows:

- Global competition: Firms no longer compete in secure domestic markets. The competition is global, as more international manufacturers have come into the picture. The race for market share, higher profits and company-survival is driving the need for new products.

- Changing customer demands: The consumer-oriented market driven by the need for high-quality, low-cost products offering unique or superior user solutions is one of the major factors responsible for new product development. Consumers have become more demanding and are expecting the products to be highly customized.

- Technology: The rapid advancement in technology is inducing the development of more and more new products and processes.

NPD has become an indispensable part of the manufacturing industry and will continue to be so in future as the factors driving NPD will continue to evolve and grow with time.

2.2 Product Innovation and Types of New Products

Innovation refers to the creation of a product, service, or process. Product innovation is the creation of new products. Product innovation can be split into different categories depending upon the degree of innovativeness. Innovativeness is the extent to which technology is applied in the creation of a new product. Types of new products are determined by the degree of their innovativeness. Based upon the literature [25,50,57,60,62], different authors have different terminology for the categories of new products, but the import of their varied terminology is essentially the same. According to relevant references [25,50,57,60,62], new products can be classified under the following headings.

2.2.1 Innovative and Incremental new products

Several authors, viz., Schmidt and Calantone, Song & Montoya-Weiss classify new products as Innovative new products and Incremental new products [50, 57].

2.2.1.1 Innovative new products

Innovative or really new products are those which are major technological breakthroughs and offer new or very unique or superior solutions to users' needs and wants while simultaneously representing new design, manufacturing and marketing challenges to the firms. Often such products may create markets that did not exist previously, spawn functional substitutes and ultimately may change the type and level of competition within the industry. The first integrated circuit, radial tire, cellular phone, personal computer and Internet services are examples of really new products.

2.2.1.2 Incremental New products

Incremental new products are not very innovative with respect to either technology or application. They involve the adaptation, refinement and enhancement of existing products and/or production and delivery systems. Incremental new products include line extensions, repositionings, cost reductions and 'me-too' products. Examples of incremental products include all modified existing products viz., Windows 2000, Pentium III etc.

2.2.2 Platform and Derivative new products

Tatikonda [60] gives the following classes of new products.

2.2.2.1 Platform new products

A 'platform' is a family of products derived from one central product design. Every new product involves some degree of change in the platform, where the change ranges from the development of a completely brand new platform to very incremental change to an existing platform. Thus the products that initiate a new product family platform are called *platform* products

2.2.2.2 Derivative new products

Products which are extensions to an existing product family platform are called *derivative* products.

2.2.3 Discontinuous and Continuous new products

Veryzer [62] categorizes new products as discontinuous and continuous. He states that innovation can be thought of as falling on a continuum from evolutionary or continuous to revolutionary or discontinuous.

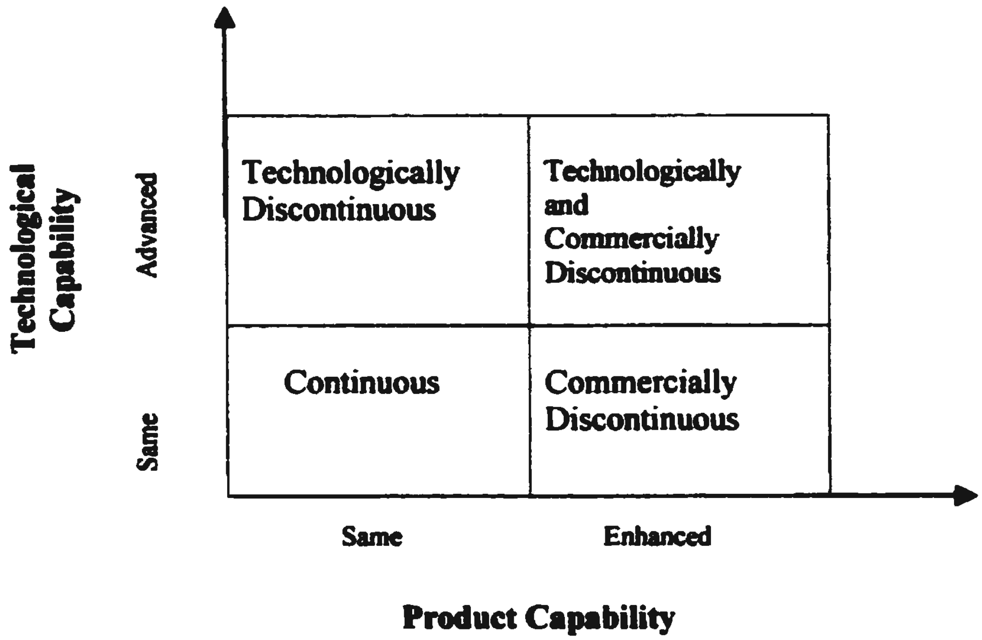
2.2.3.1 Discontinuous new products

Discontinuous or revolutionary new products are those which are radical technological breakthroughs and have considerable impact on the industry. These products involve dramatic departures from existing products or their logical extensions.

2.2.3.2 Continuous new products

Continuous new products are not very innovative and are just extensions of existing products.

Veryzer also defines a useful way of representing innovation as shown in Figure 2.1. This figure uses two critical dimensions to delineate the various levels or degrees of innovation. Product innovation can be viewed as lying along the Technological Capability dimension and the Product Capability dimension. The Technological Capability dimension refers to the degree to which the product involves expanding (technological) capabilities (the way product functions are performed) beyond existing boundaries. Discontinuous products involve advanced capabilities that do not exist in current products and cannot be achieved through extension of existing technology. The Product Capability dimension refers to the benefit(s) of the product as perceived and experienced by the customer or the user.



Product Classification Matrix
Figure 2.1

In this view of innovation there are essentially four types or levels of innovation (excluding moderately innovative products). The first type encompasses products that utilize existing technology and provide the same benefits as existing products. Such products are continuous both in terms of technology employed and the way they are experienced by customers. Although they may be new, they are not very innovative. In addition to continuous new products, new products may be discontinuous with respect to technology, the benefits perceived by the customer, or both. Products that are perceived by customers as being really new regardless of whether or not they utilize new technology are commercially discontinuous. For example, the SONY Walkman offered new benefits (i.e., functionality) utilizing available technology. In cases where the delivery of new benefits involves the application of significant new technology, the product is technologically discontinuous in addition to being commercially discontinuous. PC s and pagers were examples of this type of innovation when they were first introduced. In a few cases, products may be perceived as being essentially the same as previously existing products even though they utilize highly advanced technology. For example, the switch from vacuum tube televisions to televisions utilizing solid state technology had little impact on consumers in terms of product benefits or use. Thus, even though the solid state circuitry represented a dramatic change in technology (technologically discontinuous), the product as perceived by the consumers had changed little.

Other authors viz., Hustad [25], suggest similar classification of new products. Thus all new products belong to a product spectrum and are categorized according to varying degrees of innovation.

2.3 New Product Development Process

According to Rosenau [45], a new product development process (NPDP) defines and describes the normal means by which a company can repetitively convert embryonic ideas into marketable products and services. Such a process identifies the required steps and resources.

NPDP provides the tools to plan, schedule, manage and execute integrated NPD projects. It is a specific procedure that can be easily and dynamically tailored to the demands of a specific project as well as local circumstances.

Basically, the new product development process comprises all activities involved in developing new products right from understanding requirements, to innovating, developing and producing products which meet the needs of the customer.

The NPD process can broadly be divided into four phases:

- Market and Concept Exploration
- Design and Development
- Manufacturing and Assembly
- Product Launch, Service and Support

Different authors have their own versions of the NPD process, but most are variations of Kotler's[1] eight stage influential model: idea generation, idea screening, concept testing, market strategy development, business analysis, product development, market testing and finally commercialization [30].

---

[1] Refer Appendix 1

Also one of the most widely accepted models is the one proposed by Booz, Allen and Hamilton, based on their experience with several hundred companies [10]. Its phases are: exploration, screening, business analysis, development, testing and commercialization.

Based on research and literature review, Song & Montoya-Weiss [57] identified the following six sets of general NPD activities:

Strategic planning: Preliminary assessment and integration of a project's resource requirements, market opportunities and strategic directives.

Idea development and screening: Generation, elaboration and evaluation of potential solutions to the identified strategic opportunities.

Business and market opportunity analysis: Execution of the marketing tasks required to convert new product ideas into well-defined sets of attributes that fulfil customers' needs and desires.

Technical development: Designing, engineering, testing and building the desired physical product entity.

Product testing: Testing the product itself, as well as individual and integrated components of the marketing and advertising programs.

Product commercialization: Coordinating, implementing and facilitating the new product launch.

While these activities describe a generic NPD process, there is considerable variance in different NPD projects in terms of details of each activity. Different organizations report many different approaches to new product development process. However, the literature endorses the view that the basic structure of the NPD process is essentially the same in all conditions even though details of each activity might differ.

NPD processes can be divided into two broad categories based upon the manner in which their constituent activities are performed. The first is the traditional sequential or functional process in which the various NPD activities are carried out in a sequential manner. The other is the NPD process based on Concurrent Engineering (CE), in which the NPD activities are overlapped and concurrent.

2.3.1 Sequential New Product Development

The Sequential approach to NPD is based on the concept of Sequential Engineering (SE). It is also known as serial engineering, linear or time-phased engineering and the chimney method. Relevant references lead to the following interpretation of sequential NPD [42].

In this type of NPD, the manufacturing enterprise is traditionally broken down into functional units, departments or work centers such as marketing, product planning, design and development, and manufacturing. Each department has its own separate responsibility and functions almost in complete isolation of other departments while carrying out its activities.

For example, *Marketing* determines customer demands and needs and 'throws over' the customer specifications to the *Product planning group (PPG)* who until then have no idea about *Marketing's* activities. *PPG* then develops technical specifications for the product and again the information is passed 'over the wall' to *Design and Development*. This department then designs and develops the product on its own in near-complete isolation of *Manufacturing*. Later, the prototype is handed over to *Manufacturing* who then figure out how to manufacture the product on a large scale, and finally the product is handed over to *Marketing* for launch and sales.

Thus all activities are carried out in a serial manner with no or minimal information flow between various functions. This leads to poor understanding of customer requirements, lack of early involvement of key stake holders such as manufacturing and production engineering in initial concept design and decision making stages and a failure to utilize the expertise of suppliers effectively. Since significant trade-offs between customer requirements, product design and method of manufacture are not addressed initially, a product developed sequentially inevitably faces the following problems in terms of quality, ease of manufacture, cost and development time:

Because of lack of co-ordination between departments, product designs are often unsuitable for production in the first go as manufacturing / production / assembly problems are given little consideration in the beginning. This results in an inability to utilize existing manufacturing production equipment, tight tolerances which could lead to extra work and high scrap generation, problems with parts assembly etc. Since manufacturing issues are discovered quite late, it leads to quick-fix solutions, compromises on quality and added costs. Errors, changes and corrections take a long time to resolve often requiring that the process cycle go back to the start and proceed sequentially again. Also scarce resources are wasted on NVAs (non value-adding activities) such as error rectification, change-related documentation and progress chasing.

Many studies suggest that 50 to 80 % of the product cost is determined very early in the design process. Since, in the sequential process, design trade-offs are not considered in the beginning, it leads to higher costs.

In SE, a new activity cannot start until a previous activity has been completed and signed off. The product development time is longer not only because of this inherent nature of SE, but also because of the delay caused by various factors such as iterations in redesign, error-rectification, rework, unnecessary complexities, confusion and the development of blaming culture.

All this results in the following:

- An inefficient process with no definite structure or objective
- Protracted development time
- Long development times result in missed market opportunities and thus loss of market share
- High costs
- Low product quality
- Unsatisfied customers

This costs heavily on new product introductions where the very essence of winning the market over is a high quality / low cost new product with a short development time.

All these factors have lead to the emergence of NPD processes based on the concept of Concurrent Engineering.

2.3.2 Concurrent Engineering based NPD

Research has found that more and more manufacturing enterprises have adopted the concept of CE for introducing new products to the market. CE represents one of the most significant of the recent trends in new product development. Concurrent Engineering methodologies permit the separate tasks of the product development process to be carried out simultaneously rather than sequentially.

The most common definition of CE has been given by Winner et. al [64] ;

CE is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. The approach is intended to cause the developers from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule and user requirements [64].

Many definitions have been given since Winner. Three of these are illustrated below:

CE is a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of cooperation, trust, and sharing in such a manner that decision making proceeds with large intervals of parallel working by all life-cycle perspectives early in the process, synchronized by comparatively brief exchange to produce consensus.

CE is a product development methodology where up-front 'X-abilities' (such as manufacturability, serviceability, quality etc) are considered part of the product design and development process. X-abilities are not merely for meeting the basic functionality or a set of limited strategies, but for defining a product that meets all customer requirements [52].

CE based NPD involves all aspects of product development right from market research through design, manufacturing and product launch. This is a holistic process which encompasses parallel product development activities, cross-functional teamwork, simultaneous design of all downstream processes during upstream phases, up-front considerations of all X-abilities, maximization of quality, and, minimization of cost and total product life-cycle time [42].

In contrast to the traditional sequential approach regarding product development in which each function from design through manufacturing and all the way to distribution, is taken one step at a time in virtual isolation from its neighbors, CE advocates a rapid, simultaneous approach, where concept development, design, manufacturing and support are carried out in parallel and interactively. Potential problems in fabrication, assembly, support and quality are identified and resolved early in the design process. This results in the high quality, low cost products which can be brought to market at a faster pace.

CE has been cited as the main reason for rapid new product introductions by Japanese firms [63]. For example, a key factor behind the success of Japanese automakers is the short time they require to develop a new model with high product quality.

Japanese car manufacturers were among the first to adopt CE techniques. In the late seventies, both Honda and Mazda began operating with CE-like methods, and in 1987, Nissan followed their example. Japanese success forced US car companies to apply the technique in the mid 80's. In recent years, European firms BMW and Daimler-Benz have also started to move in the direction of implementing CE. But CE success is not limited to the auto industry only. Matsushita in Japan, Rank, Xerox, Boeing, General Electric, IBM, Digital Equipment in the US, and Philips in Europe are also enthusiastic supporters [31,63].

Several case studies cited in literature show successful implementation of CE based NPD. Viper, Chrysler (1992), Boeing (1996), Texas Instruments (1996), Cummins Engines (1996), and Xerox (1998) are some of the examples [34, 56].

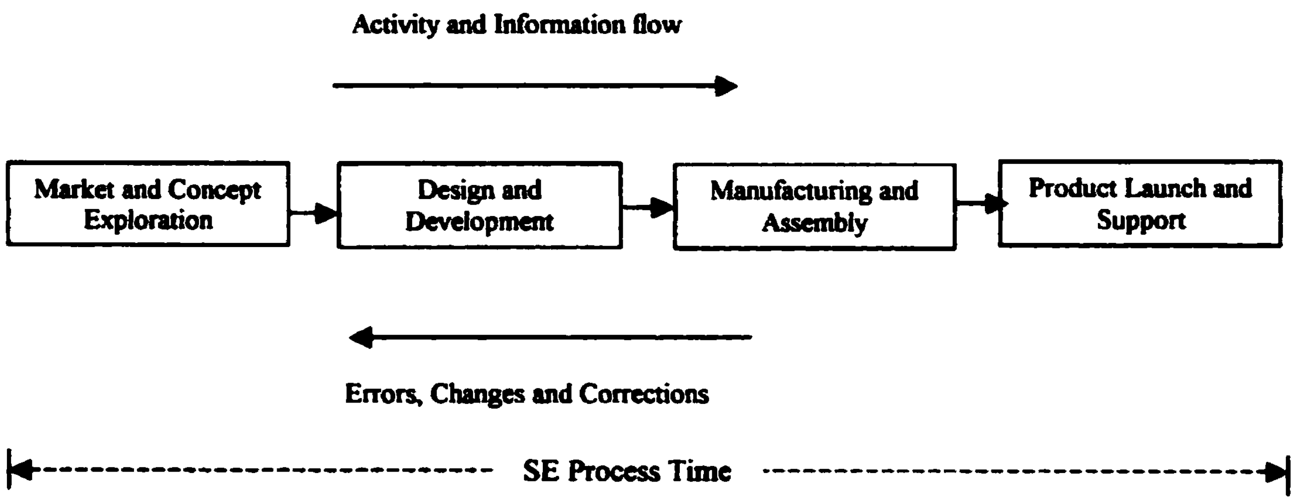
The characteristics of a CE based NPD process can be outlined as follows:

- A well defined structure and objective
- Multi-functional involvement

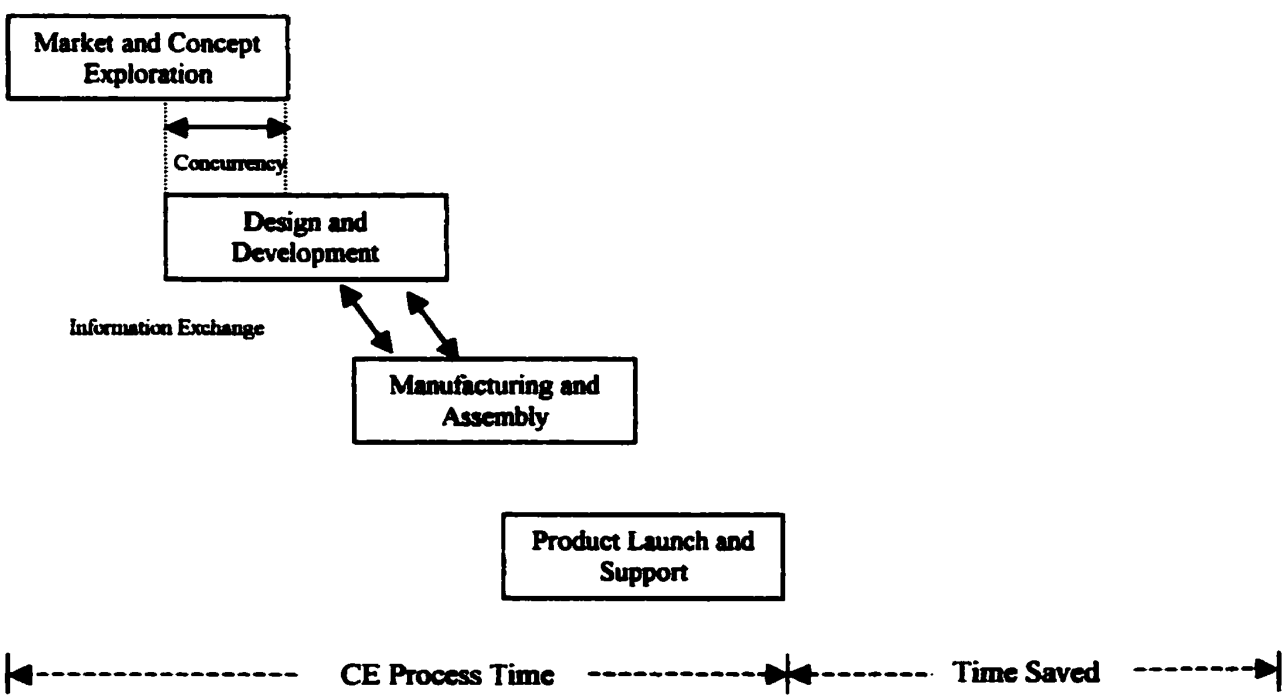
- Parallel / Concurrent activities
- Upfront consideration of downstream activities
- Focus on customer requirements
- Minimum Non value adding activities (NVAs)
- Faster development
- Low Cost
- Higher overall quality

CE is a relatively new approach and is evolving rapidly as companies gain more experience. But research shows that the organizations implementing CE are enthusiastic about the positive influences CE has had on their NPD processes, and more and more companies are adopting CE based NPD [31,34,63]. Figure 2.2 illustrates the difference between SE and CE based NPD process

Sequential Engineering based NPD Process:



Concurrent Engineering based NPD Process:



Sequential versus Concurrent Engineering based NPD Process

Figure.2.2

2.3.3 Types of CE based NPD processes

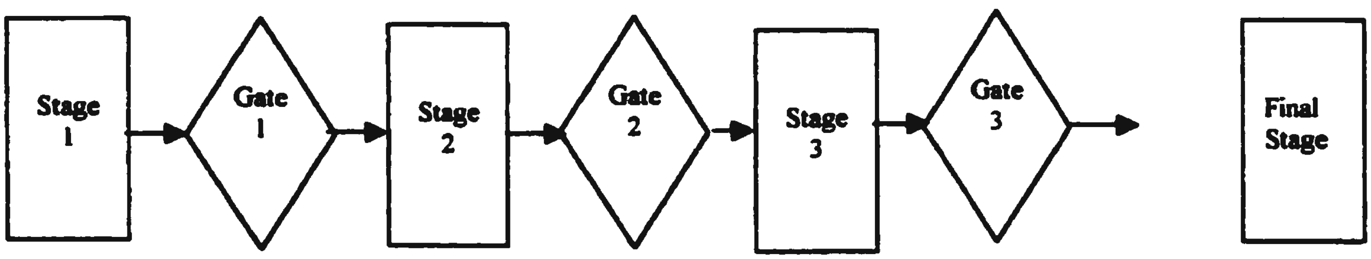
For better management of NPD, Stage-gate processes are used. A Stage-gate process effectively manages NPD by applying process management methodologies to the NPD process. Substantial literature has been developed on stage gate-based NPD processes [17, 45].

The concept of stage-gate systems is simple. It consists of two basic elements - Stages and Gates. Stages are where the work is done and the gates control the decision on workflow.

Stage: The NPD process or project is divided into sub-processes called stages. For example, the stages might be: business case preparation, product development, testing and validation and regular production, depending upon the nature of the project. Each stage signifies workflow and is composed of a group of prescribed, related and often parallel activities.

Gate: The entrance to each stage is a gate. Gates function as quality control and decision-making checkpoints, which essentially require that certain criteria must be met before the process is allowed to proceed further to the next stage. Characteristics of each gate are a set of deliverables or inputs, a set of exit criteria and an output. Inputs are the deliverables of each stage that are brought to the gate before there is any further workflow. The criteria are certain items or benchmarks based upon which the process is judged. Outputs are the decisions at the gate, which decide whether the process should move on to the next stage, be terminated, be put on hold for a while, or recycled. Cooper describes these gate outputs typically as Go/ Kill/ Hold/ Recycle decisions. Usually, a committee comprising senior management is involved in the decision-making process at the gates.

A typical stage -gate process is illustrated in Figure 2.3.



Stage-Gate NPD Process

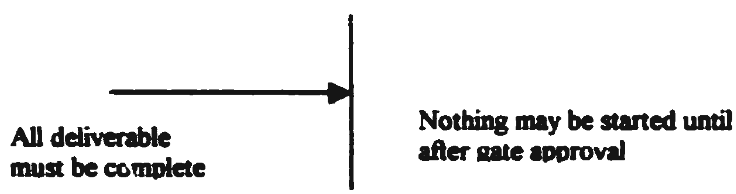
Figure. 2.3

Use of the stage-gate process is very effective because it is orderly and encourages management supervision at various appropriate times during the NPD process. When well designed and adhered to, a stage gate process assures appropriate participation by senior management when it is truly useful, especially at points where there is an incremental jump in risk or cost. During each stage, a group of tasks or activities is carried out. When these tasks are complete, a management review is conducted. If the work is satisfactory and the business case is still persuasive, the next stage is normally authorized. In some cases, the result of a stage's work is not sufficiently promising to justify continuing the effort. In this situation, the project is directed to go back, and some tasks are repeated in the expectation that more work will overcome the problems. In other cases, the NPD project is cancelled; the results to date are documented for future reference so that a decision could be taken to reactivate the project at a later date.

Further, depending upon the degree of flexibility allowed at a certain gate, the gates are classified as follows: [45]

Rigid gates

As shown Fig 2.4, for these gates, work is not allowed to proceed to the next stage until all the prior stage's work and deliverables are complete.



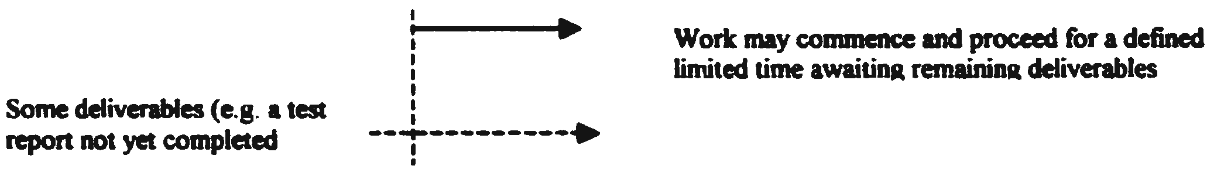
Rigid Gate

Figure. 2.4

Flexible gates

In these types of gates, work on the next stage is allowed to begin even if the previous stage is not completely finished. The flexible gates are again of two types;

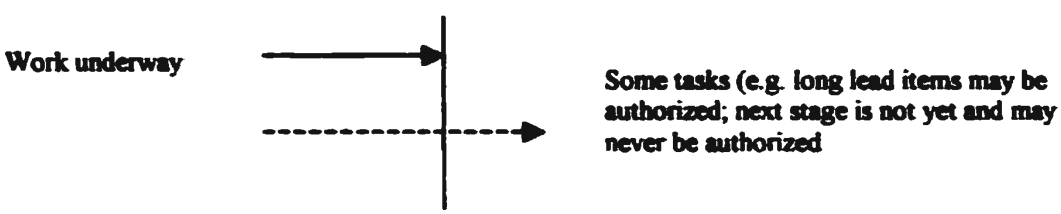
Permissive gates: As shown in Fig. 2.5, a permissive gate is one where work in the subsequent stage may begin even though some non-critical work in the previous stage is not yet complete.



Permissive Gate

Figure 2.5

Permeable gates: As shown in Fig. 2.5, a permeable gate is one where some work in a subsequent stage is authorized (e.g., most commonly the initiation of long-lead activities) even before a substantial amount of work in the prior stage is completed. When a permeable gate is authorized, it is done so as a calculated risk to save time and is not actually an early authorization to carry out more work in the subsequent stage, nor is it the justification to assure that the subsequent stage will ever be authorized.



Permeable Gate
Figure 2.6

2.4 Organizational Structure

Firms involved in product development can have different organizational structures. The structure of the organization inevitably affects the way the organization is able to introduce new products. Some of the prevalent organizational structures are briefly described in this section [12, 43].

2.4.1 Functional Organization

Here, the organization is in form of separate functions or departments such as Marketing, Design, Production etc. with each department taking care of its own specific activities. In this case a NPD project is divided into its functional components and these are assigned to the relevant function. Each function is headed by a functional manager. Co-ordination is handled by functional managers or by upper management. This type of organization endorses the 'over-the -wall' approach to NPD and basically results in an ineffective NPD process marred by lack of inter-departmental communication, lack of ownership, NVAs, longer cycle time and several other factors which lead to an inefficient NPD process. Functional structure, though still prevalent in a few organizations, has generally been superseded by more team-oriented approaches.

2.4.2 Weak Matrix Organization

This type of organizational structure is also known as the Lightweight leader form. In this case, there is a nominal leader who is devoted to the NPD project. This nominal leader (lightweight manager) has no real authority over the project and just acts as a co-ordinator. The real authority lies with the functional managers in terms of resource allocation and decision making. This form has the ability to move a project along faster than the functional form can, because the co-ordinator is responsible for drawing up schedules and checklists and monitoring compliance. However, communication and decision making in this form is just as slow as in the functional form. Thus, the weak matrix organization is not much of an improvement over the functional organization.

2.4.3 Balanced Matrix Organization

In this type of an organization, the project manager (team leader) and the functional managers have equal authority. An effort is made to strike a balance in their powers by giving the project manager control over project related matters while the functional manager retains control over developing functional expertise. This type of structure offers improvement over the previous two forms. But, it is still a difficult form to manage, because it is hard to separate the areas of authority in practice. Much time can be wasted in working out the 'turf' issues.

2.4.4 Strong Matrix Organization

In this case, personnel are recruited from functions to work on a separate full-time project team. Here, the project team is truly an independent unit within the organization. The project manager has clear authority and ownership. There is good project communication and an entrepreneurial environment. This type of structure is very conducive to the NPD process.

2.4.5 Projected Organization

In this type of structure, all resources are allocated in teams with each team taking care of a different project and reporting to its own project manager.

2.5 Tools and Techniques

There has been considerable growth in the variety and power of tools available for support of new product development projects. This section briefly lists the prevalent NPD tools. Since detailed discussion of all these tools is beyond the scope of this thesis, this section just enumerates the popular NPD tools without elaborate details. Brief definitions of these tools are provided in Appendix 2.

Following are the prevalent NPD tools in three broad categories of Marketing Research, Engineering Design and Organizational Development [25].

2.5.1 Marketing Research Tools

- Voice of Customer
- Customer site visits
- Concept Tests
- Focus Groups
- Beta Testing
- Test markets
- Pre-test markets

The above market tools are identified as potentially important tools in order of their listing. In practice however, the first three tools are the ones most often used.

2.5.2 Engineering Design Tools

- Rapid Prototyping
- Concurrent Engineering (CE)
- Design for Manufacturing and Assembly (DFM/DFA)
- Computer-aided design (CAD)
- Computer-aided engineering (CAE)
- Value Analysis
- Failure mode effect analysis (FMEA)

- Performance Simulation
- Virtual Design

Among engineering tools, rapid prototyping, CE and DFM/DFA, followed by the specific tools of CAD and CAE, have been identified as the potentially most important tools. The most widely-implemented engineering tools however are CAD, CE and DFM / DFA.

2.5.3 Organizational Tools

- Project scheduling techniques
- Champions
- Team Building Drill
- Process owners
- Heavyweight Managers
- Matrix organization
- Co-located teams

Similarly, the above organizational tools are listed in terms of their potential importance. In terms of use, project scheduling techniques are the most popular, followed by the practice of having process owners, champions and matrix organizations.

As the need to innovate is becoming increasingly more important in industry, the use of tools and techniques to achieve better, competitive new products is growing as well. This is paving way for the implementation of an increasing number of marketing, organizational and engineering techniques in NPD at present and in future.

This chapter presented an overview of the various facets of New product development. Since NPD is a complex phenomenon, the NPD process provides a tangible, structured way to realize the creation of new products. The quest towards better and more successful new products calls for an efficient NPD process. The next chapter explores this possibility and presents a NPD Process model which could achieve better and more efficient new product development.

Chapter 3

3. New Product Development Process Model

This chapter presents a comprehensive new product development process (NPDP) model designed for facilitating better and more efficient new product development. This version of the NPDP model provides an effective process to accomplish the overall development of high quality new products in a cost-effective and accelerated manner. The model is referred to as the new product realization process (NPRP) model in the chapter.

The organization of the chapter is as follows:

- NPD Process Models - an overview
- Description of the NPRP model - Features, outline and structure
- Details of NPRP phases
- Details of NPRP modules

3.1 NPD Process Models - an overview

A new product development process (NPDP) defines and describes the normal means by which a company can repetitively convert embryonic ideas into marketable products [45].

The process basically comprises all activities involved in developing new products right from understanding requirements, to innovating, developing and producing products which meet the needs of the customer.

As mentioned in previous chapters, over the last decade, manufacturing firms have been driven by high product quality, reduced time to market, low cost and high productivity goals. An effectual solution towards realizing these goals is an efficient NPD process.

Research [13, 23, 24, 56] has shown high-quality NPD processes to be associated with numerous beneficial organizational outcomes such as,

- Improvement in product quality
- Reduction in time to market
- Reduction in product development cost
- Improvement in productivity

All these factors are fundamental to successful new product development and contribute towards higher levels of customer satisfaction, early capturing of the market window, enhancement of market share and increase in profits. Thus an efficient and well-structured NPD process is a critical strategic factor for a manufacturing organization's success.

The realization that a high-quality NPD process is crucial for an organization's success has lead to research on reengineering and continuously improving the NPD process. Several NPD Models have been developed. The first model was given by Booz, Allen and Hamilton. Ever since, the NPD process has evolved over time and different steps have been added to the models to make them more exhaustive. A discussion of these models is given in Chapter 2, section 2.3. However, the models discussed in literature are fairly generic. They provide an outline of the main process phases and briefly comment on the scope of each phase.

In this chapter, we present a holistic NPD model, which gives a detailed structural framework for the NPD process of a manufacturing organization, with a focus on assembled product development. References on generic NPD models, concurrent engineering, systems engineering and project management have been sourced into the development of this model [11, 15, 17, 19, 22, 23, 24, 25, 40, 41, 43, 45, 53, 55, 56, 57].

The NPRP model exhaustively describes the process and elaborates the constituent activities, milestones and deliverables. This model can serve as an initial framework/guideline/reference for establishing a systematic NPD process in a manufacturing organization. Details of the model are provided further on in the chapter.

3.2 Description of the NPRP Model - Features, Outline and Structure

3.2.1 Features of the NPDP model

The NPRP model has the following salient features:

- Five concurrent phases (subdivided into 17 modules)
- A systemized structure with defined goals and objectives
- Extensive use of CE
- Upstream focus
- Stage gates for efficient process-control, review and management
- Tools for realizing high-quality, low-cost new products with short cycle times
- Requisite documentation

The NPRP model offers a well-structured process-model with five systematic CE based phases, which are listed and described later in the section. Extensive use of CE implies cross-functional team work (with appropriate involvement of suppliers and customers), increased communication and highly interactive, overlapping process phases. This results in optimized designs and shorter development cycles. Also, high emphasis has been placed on upstream activities i.e., the initial activities of the process, as they are crucial in determining the overall quality, cost and development time of the product. A detailed description of upfront activities is given in subsequent sections in the chapter.

The process has been well documented with features such as the process-structure diagram and input/output phase diagrams representing required inputs and expected deliverables of individual phases. Detailed description of the phases and modules is also provided. A control mechanism for reviewing progress and making significant process decisions has been incorporated through appropriate control gates or checkpoints.

Suggestions for use of pertinent tools[1] and techniques for each phase have also been provided. Since, in this NPRP model, the major emphasis is on realizing high-quality/low-cost products, the model focuses on Taguchi methods as an upstream product/process design tool to build quality products. (An intensive treatment of Taguchi methods as a NPD tool is given in the next chapter.)

All these features make the NPRP model an efficient and systematic NPDP model capable of realizing accelerated new product development with high-quality and low-cost targets.

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[1] Refer Ch.2, sec.2.5 and Appendix 2 for a listing and explanation of NPD tools

3.2.2 NPDP Model Outline

NPD is a complex phenomenon and encompasses various systems such as technology, resources, consumer-base etc. The NPRP model broadly comprises all of the system elements which go into the development of a new product. It consists of five, CE based, interdependent phases marked by appropriate control gates. The phases pertain to particular stages of the product life cycle and are further divided into seventeen modules, which constitute activities having common objectives. Appropriate reviews are conducted at the control gates before the process can proceed further.

The phases, modules and control gates are listed as follows:

3.2.2.1 Phases

- Opportunity Assessment
- Product and Process Design
- Development and Validation
- Operations
- Commercialization

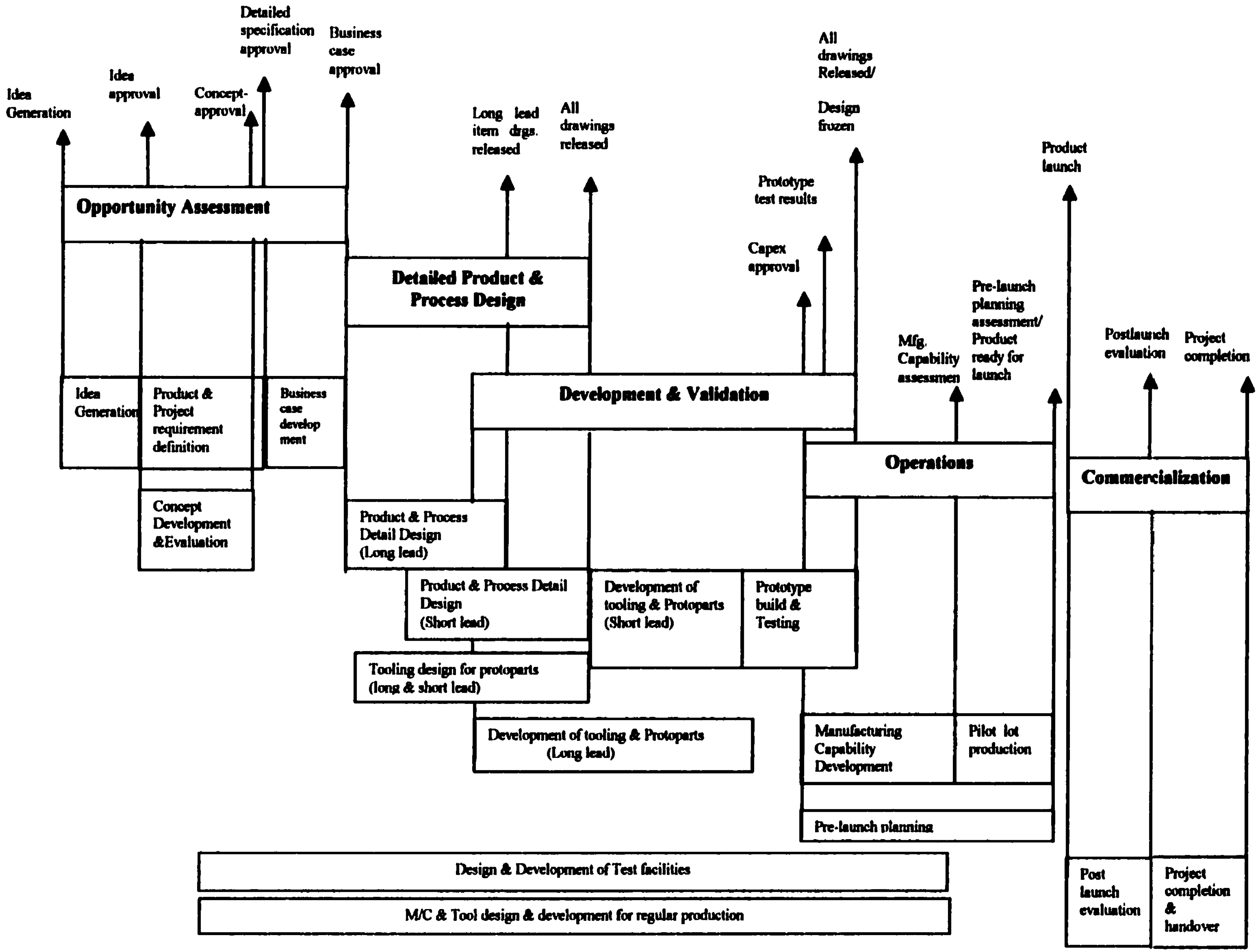
3.2.2.2 Modules

- Idea exploration
- Project and product-requirement definition
- Concept development and evaluation
- Business case development and review
- Detailed product and process design (long lead parts)
- Detailed product and process design (short lead parts)
- Tooling design (Protoparts, long and short lead)
- Design and development of test facilities
- Tooling and machine design for regular production
- Development of tooling and protoparts (long lead)
- Development of tooling and protoparts (short lead)
- Manufacturing capability development
- Pilot lot production and process refinements
- Pre-launch planning
- Post-launch evaluation
- Project completion and handover

3.2.2.3 Control gates (The subject of review at each gate is listed in parenthesis)

- Control gate 1 (Idea approval)
- Control gate 2 (Concept approval)
- Control gate 3 (Detailed Specification approval)
- Control gate 4 (Business case approval)
- Control gate 5 (Release of design - long lead items)
- Control gate 6 (Release of complete design for prototypes)
- Control gate 7 (Prototype test results)
- Control gate 8 (Capex approval)
- Control gate 9 (Total design release and Design freeze)
- Control gate 10 (Manufacturing capability assessment)
- Control gate 11 (Pre-launch assessment)
- Control gate 12 (Post-launch assessment)
- Control gate 13 (Project completion and sign off)

Figure 3.1 (p.43) gives a complete outline of the process structure and depicts the relationship between various phases, modules and control gates. The phases and modules are described in detail in subsequent sections.



New Product Realization Process Model Diagram

3.3 Description of NPDP phases

3.3.1 Opportunity Assessment [Phase 1]

This phase is concerned with the overall assessment of the new product development opportunity. The product idea is initiated, related specifications are compiled and the concept is developed during this phase. Further, a business case is prepared in order to analyse the feasibility of developing the idea into a product. The phase ends with a decision on business case sign off.

Opportunity assessment represents the so called 'fuzzy front-end' of the NPD process, since at this stage much of the information about the product is often non-existent and vaguely understood. A multitude of information has to be collected and analyzed in order to develop the product idea into a tangible concept which will eventually evolve into a real product. Opportunity assessment is that stage of the NPD process where the vital initial homework is done. A multi-functional project team representing Design, Marketing, Manufacturing, Purchase and Project management is assigned to this stage.

Though doing the pre-development work means spending more time upfront, it eventually pays off in terms of overall project clarity, reduced development time, cost-reductions and improved quality. Following are the essential benefits derived:

- Ideas which are potential winners are chosen.
- A sharp definition of the product (product specifications, features etc.) based upon customer requirements is obtained.
- A project plan with defined targets and budget is developed.
- Product/process design trade-offs are made.
- Optimal product/process concepts are developed.
- Problems are anticipated and solved earlier in the process rather than later (during development and production) when they are more costly and difficult to deal with.

The success of a new product is contingent upon the quality of information and analyses involved in upfront process activities. Thus, it is imperative that there be more upstream focus in order to realize successful new products.

Research shows that successful NPD programs spend almost twice the time upfront (approximately 44% of the total project time) as compared to the average NPD programs. Given the importance of these upfront steps, surprisingly most firms confess to serious weakness in these pre-development activities. It was found in a study that only 7% of the budget and 16% of the effort is spent on these critical steps by a majority of firms [17].

The Input/Output diagram in Fig.3.2 (p.49) gives an overview of the Opportunity Assessment phase, detailing out the objectives of the phase, the required deliverables and the inputs. An explanation of the concept of Input/Output diagram is given in Appendix 1.

3.3.2 Detailed Product & Process Design [Phase 2]

This phase is concerned with developing the detailed design of the product and the process. The concept design is developed into pre-requisites (like component drawings, process specifications etc.) required for a production-oriented design. Design of long and short lead items is completed. Tooling and machine design for regular production is initiated. Design of test facilities is also carried out concurrently.

The Input/Output diagram in Fig.3.3 (p.50) gives an overview of the Detailed Product and Process Design phase, listing the objectives of the phase, the required deliverables, and the inputs.

3.3.3 Development and Validation [Phase 3]

The main objective of this phase is to develop and validate the product and process design. Prototypes are developed and tested for performance, reliability, quality and environmental requirements. The final prototype developed at this stage is virtually indistinguishable from the intended production-unit and complete confidence in the design is established. This stage is marked by the approval of capital expenditure (capex) after confidence in design is established. The initiation of technology transfer to operations is also authorized at this stage. Design technology is frozen and released at the end of the Development and Validation stage.

The Input/Output diagram in Fig.3.4 (p.51) gives an overview of Design and Development, detailing out the objectives of the phase, the required deliverables, and the inputs.

3.3.4 Operations [Phase 4]

This phase is concerned with developing and establishing a stable production system for full-scale production of the new product. It involves the procurement of all relevant tooling, machines, material etc., and makes provision for appropriately skilled manpower. Pilot-lots are developed in this phase to validate the installed production system. This ensures that a capable production system is in place. The first regular production run is then conducted and the phase ends with the new product ready for launch. The Input/Output diagram of the phase is presented in Fig. 3.5 (p.52).

3.3.5 Commercialization [Phase 5]

This is the final phase of the NPD process. It commences with new product-launch and ends with project completion. It involves post-launch evaluation of the new product, implementation of required improvements, preparation of closure reports etc. The end of the phase is marked by a formal sign-off of the project authority to the agency responsible for regular operations. This also effectively marks the closure of the project. Figure 3.6 (p.53) gives the Input/Output diagram of the commercialization phase.

NEW PRODUCT IDEA

- Customer/ Competition / Internal / Technology-driven

MARKET

- Customer needs
- Market size / Segment
- Existing products
- Immediate and Long term market requirements

GROWTH FACTORS

- Diversification
- Possibility of a family of products
- Impact on market share
- Possibility of future growth in volume / revenue

COMPETITION

- Competitor products
- Product strategy
- Product Introduction lead time
- Product cost / features

EXISTING CAPABILITIES/ CAPACITIES

- Technological competency
- Financial capabilities
- Capabilities of Production facilities
- Resources
- Suppliers

BUSINESS

- Business strategy

LEGISLATION REQUIREMENTS

- Existing / proposed
- Domestic / international

HISTORICAL DATA

- Existing product knowledge-base
  - Technical know-how
  - Product Drawings
  - Bill of Materials (BOM)
  - Reliability/ quality issues
  - Field service concerns
  - Warranty issues
  - Past product development issues

OPPORTUNITY ASSESSMENT

OBJECTIVES

- Idea generation
- Establishing the need for the new product opportunity
- Project initiation and planning
- Detailed definition of product/process/project requirements
- Business case development and review

Recommended NPD Tools

- Voice of the customer
- Focus groups
- Surveys
- Concept tests
- Concurrent engineering
- Concept convergence
- CAD/CAE
- DFM/DFA
- Taguchi methods
- Rapid prototyping
- Cross-functional teams
- Project management

PRODUCT

- Product definition
- Definition of Detailed Product Requirements
  - Product Specifications
  - Performance criteria
  - Reliability
  - Operating conditions
  - Applications
  - Legal requirements
  - Product plan
  - Design in-house or buy
  - Product cost target estimated
  - Test requirements / specs. identified
  - BOM made
- Concept confirmed

PROCESS

- Existing mfg. capability/capacity assessed w.r.t. new product
- Rough estimate of capital requirement established
- Rough estimate of changes required in mfg. process established
- Make vs. buy items identified

SUPPLIER

- Existing / New supplier-base (capability and capacity) analysed
- Additional requirements identified
- Potential suppliers identified

MARKET

- Potential customers/ market segment identified
- Sales forecast confirmed
- Customer end price confirmed (range)
- Effect on existing product mix established

PROJECT MANAGEMENT

- Project budget / time/ deliverables approved
- Resources identified & approved
- Project plan approved
- Project Launched
- First sight estimate of :
  Capex targets, Product Cost

BUSINESS

- Feasibility report prepared
  Cost /Market/Technical/Strategic
- Business case analysed and approved

I/O diagram - Opportunity Assessment
Figure 3.2

PRODUCT

- Detailed Product Specifications
- Concept design
- Concept test feedback
- Initial BOM
- Product cost

PROCESS

- Detailed process specifications
- Concept design
- Concept validation feedback
- Estimated mfg. cost

SUPPLIER REQUIREMENT

- Existing/new suppliers' capacity/ capability
- Identified suppliers

MARKET

- Detailed Market specifications
- Confirmed Sales forecast
- Serviceability and maintainability issues

PROJECT MANAGEMENT

- Detailed Project Specifications
- Resources

DETAILED PRODUCT AND PROCESS DESIGN

OBJECTIVES

- Concurrent design of the product and process
- Design of Test facilities, tooling and machinery
- Project in execution

Recommended NPD Tools

- Concurrent engineering
- CAD/CAE
- DFM/DFA
- Taguchi methods
- Rapid prototyping
- Project management
- Cross-functional teams

PRODUCT

- BOM prepared
- Drawings completed and released
- Design verification report prepared
- Technical manual prepared
- Standardisation of parts done
- Product Cost established
- Performance specifications defined
- Proto parts mfg. planning for all items done:
  - Long lead items
  - Critical Parts
  - Short lead parts
- Design reviews conducted
- Design and Development of testing facilities initiated

PROCESS

- Make or Buy decisions taken
- Manufacturing BOM made
- Assembly Instructions prepared
- Process route sheets/ process sheets/ plant lay outs prepared and validated
- In process inspection and testing requirements identified
- Investment planning of Plant and Equipment completed
- QA requirements identified
- Planning of all tooling completed
- Tooling design initiated

SUPPLIER

- Drawings released to supplier
- Commercial negotiations completed
- Volume requirement confirmed
- Capital investment proposal made at suppliers end
- Supplier quality assurance (SQA) done
- Preliminary process design completed
- Design of m/cs initiated

MARKET

- Product design meets customer expectations
- Market segment/volume / trends finalised
- Customer end price (range) finalised
- Opportunity / Business case confirmed

PROJECT MANAGEMENT

- Project plan in execution
- Investment decision reconfirmed
- Capex proposal submitted

I/O diagram - Detailed Product and Process Design
Figure 3.3

PRODUCT

- Product specifications
- Performance specifications
- Materials specifications
- Bill of Materials
- Drawings
- Technical manual and Assembly instructions
- Plans for long and short lead part-development
- Test plans
- Testing requirements
- Testing standards
- Testing equipment and facilities

PROCESS

- Make vs. buy items
- Manufacturing Bill of Materials
- Process route sheets/process layouts/Tooling design
- Long and short lead tooling requirements
- QA requirements
- Future Planning Requirements

SUPPLIERS

- Component drawings
- Process route sheets/layouts/ M/c and tooling design
- QA requirements
- Commercial negotiations

MARKET

- Field test plans made

PROJECT MANAGEMENT

- Project plan execution feedback
- Risks / issues (if any)

DEVELOPMENT AND VALIDATION

OBJECTIVES

- Prototype production assembly and validation
- Validation of product and process design
- Design and development of test facilities, machinery and equipment
- Initiation of pre-launch preparation
- Project execution and control

Recommended NPD Tools

- Concurrent engineering
- CAD/CAE
- DFM/DFA
- Taguchi methods
- Rapid prototyping
- Alpha/Beta testing
- Project management
- Cross-functional teams

PRODUCT

- Prototype assembled
- Prototype tested
- Product design validated after all tests
- Test results checked against performance criteria
- Confirmed BOM
- Technical manual updated
- Product design proven and frozen
- Product cost established
- Pilot lot schedule made

PROCESS

- Process finalised and verified
  - Process sheets
  - Mfg. BOM
  - Layouts
  - QA requirements
  - Capex decision
- Bottle necks defined
- QA requirements defined
- Assembly Problems identified
- Test facilities installed
- Tests results verified
- Maintenance plans made
- Procurement of tooling and machinery started

SUPPLIERS

- Proto parts made and tested
- Process design verified
- Testing facilities installed
- Investment decision made and procurement of additional tooling and machinery started
- Volume and capacity requirement confirmed
- M/C and tooling design and development (on-going)

MARKET

- Field testing at customers end
- Feedback for improvement
- Pre-launch planning initiated /requirements identified
- Interaction with concerned launch-agencies started

PROJECT MANAGEMENT

- Project progress reviews
- Risk / progress reports

I/O diagram - Development and Validation
Figure 3.4

PRODUCT
- Product specifications
- Drawings
- BOM
- Technical manual
- Assembly Instructions
- Product cost

PROCESS
- Process design/documentation
  - Process flow charts/route sheets
  - Layout plan
  - Production schedules
  - Mfg. BOM
- Machinery /tooling/equipment
- In-Process testing requirements
  - Test equipment
  - Test procedures
- Raw materials / components / sub-assemblies
- Training plans for plant-personnel

SUPPLIERS
- Process design /documentation
  - Process flow charts/route sheets/ Layout plan
  - Production schedules
  - Mfg. BOM
- Machinery /tooling /equipment
- In-Process testing requirements
  - Test equipment/procedures
- Raw materials / components / sub-assemblies
- Training plans

MARKET
- Inputs for pre-launch preparation
  - Product features
  - Marketing strategy (price/ segment / volume)
  - Final confirmed sales forecast
  - Product promotion requirements
  - Service requirements
  - Logistics requirements
  - Distribution requirements
  - Training requirements

PROJECT MANAGEMENT
- Project progress feedback
- Risk / hazards

OPERATIONS

OBJECTIVES

- Establishment and verification of Manufacturing capability (Pilot/Regular)
  - Emplacement of all mfg.facilities (Including m/cs, tooling, test equipment etc.)
  - Pilot lot manufacturing and testing
  - Product and Process design verification
  - Manufacturing Process technology freeze
  - Technical transfer to operations
  - Establishment of regular production capacity
- Completion of pre-launch preparation
- Project Execution & control

Recommended NPD Tools
- Concurrent engineering
- CAD/CAE
- DFM/DFA
- Project management
- Cross-functional teams

PRODUCT
- Pilot lot made
- Pilot lot tested (lab/field tests)
- Design meets all requirements
  - Customer requirements
  - Mfg. requirements
  - Legislative requirements
  - Serviceability/maintainability
- BOM finalised
- Operator/ repair-manual prepared

PROCESS
- Process design/documentation finalised
- Machine and tooling installed
- M/c and tooling trial results obtained
- In-process testing facilities installed
- QA requirements met/ Maintenance plans made
- Training of personnel completed
- Production schedules made
- Manufacturing BOM finalised
- Process frozen
- Technical transfer to operations
- Mfg. Capability established and validated
- Regular production started

SUPPLIERS
- Process design / documentation finalised
- Machine and tooling installed
- M/c and tooling trial results obtained
- In-process testing facilities installed
- QA requirements met
- Production schedules made
- Process frozen

MARKET
- Launch plans made:
  Timing and positioning plans/ Training plans/ Logistics plans/ Advertisement plans
- Sales volume confirmed
- Launch dates and places confirmed
- Advertisement started
- Launch documentation prepared (service/operator's manuals/sales pamphlets etc.)
- Training completed:
  - Sales/service staff
  - Dealers -sales/service staff
- Distribution network in place
- Product shipment started

PROJECT MANAGEMENT
- Project progress reviews
- ent in place

I/O diagram - Operations
Figure 3.5

PRODUCT

- Product launch commences
- Established product design technology
- Documentation

PROCESS

- Established process technology/ documentation
- Regular production underway
- Future production schedules

SUPPLIER

- Established process technology/ documentation
- Regular production underway
- Future production schedules

MARKETING

- Product launch commences
- Established product-launch capability

PROJECT MANAGEMENT

- Project execution/completion plans
- Project data/ documentation

Commercialization

OBJECTIVES

- Product launch (Initiation / feedback/ completion)
- Project execution and completion
  - Formal handover to Regular product development unit
  - Technical support to operations for a stable regular production system
- Product / process performance appraisal
  - Actual product performance measured against target
  - Plans for continuous improvement

Recommended NPD Tools

- Concurrent engineering
- Test markets
- Project management
- Cross-functional teams

PRODUCT

- Product launch completed
- Customer expectations met
- Product feed back started
- Problems (if any), identified
- Product strategy updated
- Warranty requirement defined
- Product design technology confirmed

PROCESS

- On going full scale production
- Quality and productivity improvement plans made, if required
- Maintenance plans executed
- Process capability /technology confirmed
- Future production schedule made
- On-going continuous improvement

MARKET

- Launch feed back
- Competitors activities
- Dealers confidence level gauged
- Continuous training of dealers and mechanics
- Warranty requirements noticed
- Spare parts lead time established
- Future sales forecast projected

BUSINESS

- Business objectives met
- Potential profit confirmed
- Future expansion plans
- Future investment plans

PROJECT MANAGEMENT

- Project completion report made
- Project handover to Regular product development group/Formal project completion and sign off

I/O diagram - Commercialization
Fig. 3.6

3.4 Description of NPDP modules

3.4.1 Idea Exploration [Module 1]

This module is concerned with the initiation of a product idea and preparation of a 'first glance' business case for exploring its feasibility. The module ends with the decision on whether the idea should be approved or not. Idea Exploration involves the following activities:

3.4.1.1 Idea Initiation

The idea for a new product can be generated by any number of sources viz., the customer, R&D, other internal departments, employees, competitor-products etc.

3.4.1.2 Preliminary Assessment

Usually, organizations have Product planning groups (PPG) or similar agencies to which new product ideas are siphoned for further processing and assessment. These agencies consist of cross-functional, senior-management members, who have considerable expertise and experience in company goals, strategies, competencies and strengths.

The ideas are screened and assessed through judgmental evaluation and discretion of the group members. At this stage, the evaluation is primarily based upon internal available data.

The typical assessment steps are briefed as follows:

3.4.1.2.1 Market Assessment

The purpose of this step is to review the idea with respect to the market, customer and competitors, in order to assess the market-need for developing the new product.
Following issues are raised:

- Why is the new product required?
- What is this new product all about? (Preliminary definition)
- What are its major benefits to business?
- What are the major customer requirements?
- What is the estimated sales volume?
- What is the target market segment?
- Is a similar product already in the market?
- How will the product fare in competition?

The answers to above questions help outline the target customer, potential market segment, a rough-cut sales forecast, price range and the degree of competition. If this information is compliant with the firm's strategy and points towards a lucrative market potential, then the idea is considered to have feasible market aspects.

3.4.1.2.2 Technical Assessment

The purpose of this activity is to evaluate existing technical capabilities (design/mfg. process/supplier-base) in the context of the new product, in order to get an initial idea as to whether the new product is technically feasible at all. If it is, then the degree of change or technical augmentation required can be estimated.

Information on existing capabilities is outlined in order to establish how the new product can be realized within the existing setup, with or without major changes/investments:

3.4.1.2.2.1 Existing product technology (In house/Suppliers/Joint ventures)

- Product design knowledgebase (includes information on product features/ specifications etc.)
- Design tools and facilities
- Manpower availability

3.4.1.2.2.2 Existing Process Technology (In house/Suppliers/Joint Ventures)

- Process flow layouts
- Number of machines and their capabilities/capacities
- Bottlenecks
- Tooling facilities
- Manpower availability

A rough estimate of initial product requirements in terms of technical functionality, features, process requirements etc. is prepared and feasibility analysis is done in the context of the existing capabilities.

3.4.1.2.3 Strategic Assessment

The idea is assessed to evaluate its compliance with the organization's business strategy. The business strategy of an organization gives an idea about the direction in which the business wants to grow. It provides information on the following:

- Mission, goals and objectives of the organization
- Market strategy (in terms of type of products/market sectors/customers etc.)
- Pricing policy
- Future plans

A new product should comply with an organization's business strategy in order to be successful. It is examined to see whether the new product definition, technology, price range, intended market segment etc. are in conformance with the business strategy.

3.4.1.2.4 Commercial Assessment

The idea is evaluated on the basis of commercial feasibility to determine whether it is economical and viable, with an acceptable business risk. This includes analysis of the following in brief:

- Capex requirements
- Achievable target dates
- Return on Investment (ROI)
- Commercial risks

3.4.1.3 Idea Approval

Only ideas which pass the above feasibility assessment are approved and allowed to proceed for further exploration. Idea screening is usually done by the Product planning group or Project committee or another similar agency in the organization. When an idea has been approved, a cross-functional project team is assigned to develop the idea further. The team works jointly through workshops and team meetings. Having a co-located team can greatly improve communication and information-flow.

3.4.2 Project and Product Requirement Definition [Module 2]

The purpose of this module is to develop detailed requirements concerning different aspects of the new product idea. Information on marketing, product/process and project requirements is gathered and further developed into appropriate specifications.

This module is highly interactive with module 3, viz., Concept development and evaluation. There is a continuous, mutual flow of information across these modules. The initial concept is interactively developed based on product requirements and, as the concept evolves, the product specifications might require modifications as well. After the concept is finalised, changes might need to be incorporated into the detailed specifications based upon the concept-evaluation feedback. Following these changes, the specifications are also finalised.

The module consists of the following activities:

3.4.2.1 Detailed Market Specification Development

An in-depth market research is conducted at this stage. Customer requirements are determined. Surveys, face-to-face interviews with customers, focus group studies etc are conducted. The following information is compiled:

3.4.2.1.1 Identification of Potential markets

This is defined based on the following factors:

- Need for the product
- Prospective customers
- Present market segment
- Sales forecast
- Existing supply
- Domestic and international price trends
- Technology trends

3.4.2.1.2 Customer Requirements

The following information is compiled:

- Expected features
- Price
- Quality
- Safety issues
- Warranty concerns

3.4.1.1.3 Competitor Analysis

This involves the following:

- SWOT (strength/weakness/opportunity/threat) analysis of competitor products
- Future strategy
- Market share
- Benchmarking w.r.t., Cost, Quality, Product introduction lead time, technology, features etc.

3.4.2.2 Detailed Product and Process Specification Development

In this step, customer requirements are translated into product and process requirements, and, product and process specifications are worked out.

3.4.2.2.1 Product Specifications

These comprise the following information:

- Product features
- Functions
- Performance requirements
- Potential material considerations
- Critical components
- Make or buy decisions on components

- Operating environment
- Reliability, Quality requirements
- Testing requirements
- Relationship with existing products
- Legislative / regulatory requirements
- Product cost target (estimated based upon product features, volume, pricing policy etc.)

3.4.2.2.2 Process Specifications

These comprise the following information:

- Process capacity
- Make or buy decisions on components (selection of potential suppliers)
- Type of Mfg. Processes required
- Critical process steps
- Machines required
- Tooling considerations
- Quality control requirements
- Changes required
- Capital investment target (estimated based upon product specs, process requirements, mfg.capability etc.

3.4.2.3 Detailed Project Specifications Development

In terms of operating the whole project, detailed project specifications are developed. These include the following:

- Project plan outlining major workpackages and milestones
- Project budget
- Resource plan
- Project deliverables

3.4.3 Concept Development and Evaluation [Module 3]

This module deals with the development and evaluation of product and process concepts from which the final design will eventually evolve. As mentioned earlier, this module proceeds concurrently with module 2.

Product and process concepts are designed simultaneously in order to ensure that:

- Product design incorporates all aspects of manufacturability (in-house/supplier)
- Maximum use of existing manufacturing capability is made
- Manufacturability issues are identified, resolved and changes/solutions are incorporated in the new process concept
- Commitment and confidence of downstream personnel and suppliers is gained

- Overall project duration is reduced

Different concepts or basic product/process architectures are considered, and the concept which leads to optimal product/process design is finally selected. The module is crucial to the NPD process as a sound design depends on a sound concept.

Concept design is developed through cross-functional liaison, based on the available information on customer requirements, product/process requirements and specifications. There is a high degree of interaction in the cross-functional team involving personnel from design, manufacturing, purchase/suppliers and marketing. Information is continuously refined based upon interactive feedback in order to arrive at an optimal design concept.

3.4.2.1 Product Concept Design

The major objective of Product concept design is to translate the new product idea into a tangible entity such that the idea can be better understood, communicated and evaluated.

As discussed earlier, in product concept design, fundamental customer requirements and product specifications are translated into a design concept. References to existing products and processes are made to ensure utilization of the existing knowledgebase.

The degree of detail required in new product concepts can vary depending upon the amount of clarity required, the information available, the cost involved and the purpose of the evaluation. Often cost/detail trade-offs are made based on requirement. Concept models can range from sketches to working models contingent upon the situation.

Concept design may include the following features:

- Simple written descriptions
- Layouts / Sketches
- 3D models (cardboard /clay/computer generated/rapid prototype)
- Mock ups of selective critical features/sub-assemblies
- Preliminary Bill of Materials

3.4.2.2 Concept Testing

The main aim of concept tests is to see whether the idea is workable and can actually be translated into a real product. Different methods are used for testing the product concepts depending upon the situation and complexity of the concept model. Following activities are involved in the area of concept testing:

3.4.2.2.1 In-house Concept Tests

These tests are basically done to demonstrate the technical feasibility of the new product idea. It may involve the following:

- Testing of certain selective critical features or sub-assemblies
- Computer simulated analysis (Stress/Thermal analysis etc.)

Also at this stage a rough outline of the test plans can be prepared which can be used as a reference for future testing considerations.

3.4.2.2.2 Consumer Concept Tests

Consumer concept tests may be carried out by conducting focus group studies, market surveys, mail surveys, trade shows etc. These tests are done to gauge consumer reaction to the new product concept. They provide the following information:

- Acceptability of the product
- Features liked and disliked by the consumer
- Additional expectations from the product
- Improvements suggested
- Purchase intentions
- Price range

- Potential market segment
- Potential sales

This information is very helpful in deciding whether the new product idea is promising or not; and if it is, how can it be further improved. The concept is finalised depending upon its feasibility.

3.4.2.3 Process Concept Design

This stage involves comprehensive development of an effective manufacturing system concept which ensures that the customer requirements and product specifications are met. The existing system is studied and assessed in light of new process requirements and suitable modifications/changes are incorporated into the design of the new process. Various alternatives are considered and evaluated in order to arrive at the optimum process which fulfils all requirements. Following activities are included in this phase:

- Identification of Make vs. Buy items
- Capacity considerations
- Process flow models incorporating systematic representation of the proposed process flow from the beginning to the end of the process. These will consider all aspects of the process viz., m/cs, material, methods, quality control and manpower.
- Route sheets for the various components

- Tooling requirement
- Solutions for existing bottlenecks
- In-process testing considerations
- Capital investment requirements

Based on product concept design and capital investment targets, the optimum process concept is selected reviewed and finalised. Process concepts can be tested using computer-simulated models.

3.4.2.4 Bill of Materials

At this stage, a preliminary BOM is prepared based on the product and process concept and specifications. The BOM is a detailed list of parts required for building the product. It contains part numbers, drawing numbers, material specs etc. In subsequent phases, this BOM is refined and updated as design progresses further.

3.4.2.4 Cost Estimate

A fairly accurate estimate of the product cost can be prepared at this stage. The concept component drawings and BOM can provide the following information which can be reviewed by involved functions for cost calculation purposes:

- Overall size/ Weight of the component
- Material

- Manufacturing operations required
- Quantity
- Other relevant information

For example, this information can be used by Purchasing for appraising material costs and the cost of components/sub-assemblies being purchased from suppliers. Manufacturing can utilize the information for studies related to process layout, material handling, m/c and tool utilization, labor requirements, processing time etc. The data obtained from the studies is further used to calculate related costs, and ultimately, reasonable estimates of product cost and capital expenditure.

3.4.4 Business Case Development and Review [Module 4]

A business case is developed based upon the information compiled in modules 2 and 3. Detailed feasibility-analysis of Marketing/Technical/Commercial aspects is conducted. A senior management committee reviews the business case. This marks the end of the module with a decision point for business case sign off, which gives permission for design and development of the new product.

3.4.5 Detailed Product & Process Design (Long-lead parts) [Module 5]

This module involves the following activities:

3.4.5.1 Detailed Product Design

The design of the items with long-lead development times is initiated first in order to allow ample time for their development and thus avoid delays in the project schedule.

The main tasks involved are:

- Complete design planning for long lead items
- Detailed drawing preparation
- Engineering specification preparation
- BOM preparation
- Design verification
- Design review
- Release of design

3.4.5.2 Detailed Manufacturing Process Design (in-house and supplier)

Process design is taken up simultaneously along with product design in order to reduce the overall time of the process and ensure better design trade-offs.

The concept process-flow plan is further elaborated. The product-manufacturing route is confirmed, and details of each operation are provided. Details of all equipment, tooling and gauges are also identified at this stage.

This stage involves the following steps:

- Confirmation of make vs. buy items
- Confirmation of capacity requirements
- Preparation of detailed manufacturing process plan
- Details of process equipment, tooling and gauges
- Creation of process sheets
- Definition of process parameters (viz., speed, feed, tool changing frequency etc.)
- Description of in-process inspection checkpoints
- Description of process quality procedures
- Preparation of assembly instructions
- Preparation of Mfg. BOM
- Capital expenditure plans

3.4.6 Detailed Product and Process Design (Short-lead parts) [Module 6]

Short-lead items are those which are not critical to process lead-time and can be developed in normal time spans.

The activities for this phase are similar to those in the previous phase.

3.4.7 Tooling Design (Proto-parts, Long and Short-lead) [Module 7]

During the Concept design stage itself, the tooling needs are outlined. Make/Buy parts are identified, and the tooling which has to be developed in-house or at the supplier's end is also identified.

Tooling design is initiated during the component design stage for achieving better design trade-offs and concurrency through interaction between the component designer and the tooling designer.

Tooling design involves:

- Design of tools
- Design of jigs and fixtures
- Design of gauges/ measuring equipment

Again, the tooling for long lead and critical protoparts is designed first so that it is developed well in time for manufacturing the critical protoparts.

3.4.8 Design and Development of Test Facilities [Module 8]

The outline of test-requirements is developed during concept testing. Feedback received from concept tests forms the basis for further expansion. The design of test facilities is initiated after the concept design is finalized, and should be completed before the start of prototype testing.

The steps in this module may be consolidated as follows:

- Identification of product features that require testing
- Identification of product parameters
- Identification of performance parameters
- Specification of required values of product and performance parameters
- Reference of test standards
- Ensuring that the specified values meet standard requirements
- Identification of in-house test facilities
- Identification of outside test agencies which can be hired for tests that require special expertise or equipment not available in-house
- Identification of test facilities and equipment that needs to be designed and developed (e.g. test rigs)

- Preparation of detailed test plans specifying various criteria like test sequence, time frame, resources etc.
- Detailed definition of test procedures for the various tests
- Development and procurement of required test facilities

3.4.9 Tooling and Machine Design for Regular-Production [Module 9]

The purpose of this module is to design the tooling, gauges and machines required for regular production. Discussions on tooling/machine-design are initiated with the suppliers, concurrent with product and process concept design. Involvement of suppliers early in the process helps bring in their expertise, and thus better design trade-offs can be reached. This module consists of the following activities:

3.4.9.1 Machine and Tooling Identification

During the concept design stage, the need for new machines and major tooling is identified based on product-requirements (such as specifications, features, production rate, quality parameters etc.)

3.4.9.2 Discussions with Suppliers

The product concept and component drawings are discussed with potential suppliers. Quotations are invited and suppliers identified. Machine-specifications are prepared and reviewed.

3.4.9.3 Machine and Tooling Design

Based on specifications, the machine/tooling design is initiated. Progress in design is continuously monitored and reviewed by the team, and suggestions are made for design refinement. Machine design is completed and approved after refinements based on feedback from prototype-finalization are incorporated into the design.

3.4.10 Development of Tooling & Protoparts (Long-lead) [Module 10]

This module is concerned with the development of long lead tooling and protoparts. It is pursued concurrent with product and process design. Some of the tooling and protoparts may be developed in-house and some by the supplier depending upon available capacity / capability, ease of development, cost, quality and time requirements. Following are the major tasks involved:

- Development of tooling (in-house)
- Development of tooling (by supplier)

- Tooling inspection and trials
- Development of protoparts

Prototype components are developed after the tooling has been developed. However, the development of some protoparts (if any), which can be made out of existing tooling, can be initiated earlier.

3.4.11 Development of Tooling & Protoparts (Short-lead) [Module 11]

This module is concerned with the development of short-lead tooling and protoparts. The activities in this module are similar to those in Module 9, with the difference that here the development of the remaining tooling and protoparts is done.

3.4.12 Prototype Assembly and Testing [Module 12]

The objective of this module is to build and test the prototype and thus verify the design w.r.t. the product requirements defined in the opportunity evaluation phase.

3.4.12.1 Prototype-assembly

The components are received, inspected and assembled into prototypes. The following useful information can be obtained during this activity:

- Ease of assembly/dis-assembly
- Time required to assemble/dis-assemble a particular component
- Number of tools required
- Time taken to repair a possible fault

This provides information on the assembly and serviceability aspects of the product and verifies how conducive the design is for assembly during regular manufacturing.

3.4.12.2 Review with Internal/External customers

The prototype assembly results are reviewed with people across the business to share their views & make them aware of the new product. Key customers/dealers/ field-service personnel must be asked at this stage for their opinions of the new product.

3.4.12.3 Prototype Testing

The assembled prototypes are then be tested for performance, reliability, quality characteristics etc., according to agreed test plans. The type of tests performed may include the following:

- In-house tests (alpha tests)
- Fields tests (beta tests)
- External agency tests (regulatory tests)

3.4.12.4 Analysis of Test-Results

Prototype test-results are analyzed, reviewed, and checked against the acceptance & performance criteria. Areas that need improvements in product as well as process design are identified.

3.4.12.5 Design Freeze

The design / drawings are revised as required. The total design-package is frozen at this stage and is ready for release for pilot-lot production.

3.4.12.6 Capital Expenditure (Capex) Approval

Regarding the capex approval for procuring machinery and tooling, the business has three options:

- No Risk

  Capex is approved only after prototype testing is complete and the design has been thoroughly verified.

- Maximum Risk

  Capex is approved and orders placed for procurement of regular tooling/ machines just after design release for prototype-development.

- Calculated Risk

Capex is approved at an intermediate stage of prototype testing, when a fair amount of confidence has been established in product and process design, especially for critical parts.

The option selected would depend upon:

- Selective testing already done to resolve the areas of concern (e.g. simulated product testing for strength, endurance etc.)
- The degree of risk the business can take regarding investment and time considerations etc.

3.4.12.7 Compilation of Total Technical Data

Based on test results and the final design, total technology is updated in a technical manual which is released to various departments.

3.4.13 Manufacturing Capability Development [Module 13]

The module is concerned with the development and installation of the manufacturing capability required to produce the desired product.

3.4.13.1 Machinery and Tooling Development for Regular Production

The development of tooling and machinery is still underway at this stage. Some modifications / refinements in design might be required depending upon the results of prototype testing. The sign off for machine/tooling procurement is already given with Capex approval.

3.4.13.2 Training for Plant/Product Support Unit

Plant personnel involved in actual manufacturing of the new product are trained in order to make them conversant with the product design and process.

3.4.13.3 Establishment of Plant-Layout

It is ensured that the planned plant-layout is in place and provisions for installation of new machinery are made before it actually arrives at the plant. (e.g., m/c foundations may be prepared, required electricity/water connections installed etc.)

3.4.13.4 Receipt /Installation/Inspection of Machines and Tooling

After necessary inspection at the supplier's end, tooling and machines are received at the plant and installed as per layout. Requisite inspection and trials are conducted to establish the machining capability.

3.4.13.5 Planning for Pilot-lot Manufacturing

Timing schedule, inventory plan for pilot-lot production is prepared.

3.4.14 Pilot-lot Production and Process Refinements [Module 14]

This module is concerned with verifying and validating the Operational capability in order to ensure that a quality manufacturing process is in place before the first production run is carried out. This is achieved through pilot-lot manufacturing. Pilot-lot runs are used to install the process, finalise the training of production-personnel and confirm that the required process capability has been achieved before regular production commences. The following activities are involved:

3.4.14.1 Pilot-lot Run (1)

Pilot lot run (1) is the trial run. It is conducted using regular production facilities, regular tooling and manpower. This run provides the following feedback:

- Manufacturing-system evaluation
- Process capability evaluation
- Issues/concerns/deviations observed during manufacturing/assembly

This feedback provides vital information for future refinements and improvements in operational capability.

3.4.14.2 Pilot-lot Run (2)

Feedback from the trial run is incorporated to resolve concerns and improve the process. Pilot-run (2) is then carried out to confirm the resolution of all concerns.

3.4.14.3 Pilot-lot testing

The pilot-lots are tested through in-house and field tests in order to confirm the product performance and quality.

3.4.14.4 Pilot-lot Run (3)

Feedback from Run 2 and pilot-lot tests is further incorporated to improve the process. Run 3 is then carried out to confirm the final process.

It is ensured that the manufacturing capability meets the required criteria in terms of quality, cost, volume and time.

3.4.14.5 Ramp up for Regular Production

After the pilot-lots have been run and manufacturing capability established, the process technology is frozen and released for regular production.

3.4.15 Pre-launch Planning [Module 15]

This module involves planning and facilitating the introduction of the new product into the market. The success of a new product introduction is greatly dependent on its pre-launch planning. Pre-launch planning may be initiated concurrent to prototype testing and will run parallel to 'Manufacturing capability development' and 'Pilot-lot production' modules.

Overall tasks involved are consolidated as follows:

- Launch plan preparation (detailing information on target markets, distribution channels, launch dates etc.)
- Advertisement planning
- Development of dealers' facilities
- Preparation of launch material (Operator's manual, Service manual, Spare parts list)
- Training of Sales/Field-service support personnel

- Logistics planning
- Confirmation of final sales forecast
- Advertising and promotion

The module ends with completion of all preparations for product-launch. At this stage, the new product is ready for launch.

3.4.16 Post-launch Evaluation [Module 16]

The module commences with the new product-launch. The product is available in the market and sales begin.

Post-launch evaluation of the new product is concerned with assessing the marketplace response to the product and evaluating the success of the launch across all aspects of the operational capability.

This module comprises the following activities:

3.4.16.1 Market Appraisal

Market appraisal is conducted to gauge the market reaction. This involves information on product-sales, consumer-response, competitive-response and product-improvements required.

3.4.16.2 Manufacturing Process Appraisal

The manufacturing process is evaluated to see if the process is delivering as required and if any improvements are necessary.

3.4.16.3 Support Systems Appraisal

An evaluation of support systems such as service, maintenance, spare-parts distribution etc., is conducted to assess the quality of their function and determine any improvements required.

3.4.16.4 Project Appraisal

An evaluation of project deliverables, time, cost and quality targets is conducted to assess the project success.

3.4.16.5 Launch-process Appraisal

An appraisal of the launch-process itself is done in order to evaluate the mechanism and quality of the current process and ascertain improvements for future launches.

3.4.16.6 Sales Appraisal

Generally the initial sales-pattern takes around six months to stabilise. Forecasts for future sales are determined based on the stable sales-pattern.

3.4.17 Project Completion and Handover [Module 17]

This module marks the completion of the new product development process. The project is handed over by the product development team to the Product support unit (responsible for on-going regular product development) during this period. During the transition of the project, the development team and the product support unit jointly ensure that all aspects of operation are in place, the manufacturing process is delivering and a quality-product is being manufactured. As the development team gradually withdraws support, it is ensured that all aspects of the project are understood by the receiving agency, so that it is successfully able to execute its responsibilities in the future. A formal sign-off marks the transition of authority. From this point onwards, the Product support unit is responsible for the product and concerned operations.

The following activities are involved in this module:

3.4.17.1 Project Report Preparation

Activities, experiences, highlights and results of the whole project life-cycle along with appropriate suggestions for continuous improvement are consolidated into a project report. The following information may be included:

- Adherence to targets (in terms of specifications, deliverables, cost, and time)
- Deviation from targets
- Reasons for deviation
- Profits against target
- Problems faced
- Unresolved issues
- Lessons learnt

This project report can serve as a reference document for future projects. The report is retained for project records and copies are submitted to Management and the Product support unit.

3.4.17.2 Preparation of Plans for Continuous Improvement

Plans for continuous improvement of both the product and the process are made and finalized.

3.4.17.3 Confirmation of Operational Capability

Complete confidence in the operational capability for delivering a quality-product is established.

3.4.17.4 Project Handover and Sign-off

The development team formally hands over the project to the Product support unit in a top-level, sign off meeting. This marks the completion of the new product development project. The development team either disbands or takes over another project depending upon management direction. However, the expertise of the team may be called upon in future by the Product support group to deal with issues related to the project.

In this chapter a detailed description of the NPRP model for realizing successful new product development was given. It was briefly mentioned that the NPRP model would focus on Taguchi methods as a quality tool for achieving high-quality/low-cost products at an accelerated pace. The next chapter deals with Taguchi methods and the scope of their application in new product development.

Chapter 4

4. Taguchi Method and the Potential of its Application as a NPD Tool

The major objective of the NPRP model developed in Chapter 3 is to facilitate accelerated new product development characterized by high quality and low cost. The model has been suitably structured to realize this objective. The emphasis of the NPRP model is on the process front-end, where the maximum benefits in terms of high product quality and low cost can be achieved in addition to an accelerated development pace. The NPRP model advocates the use of Taguchi method (TM) as a special product/process design tool to achieve high-quality/low-cost NPD. Although TM can be used as a quality tool throughout the NPD process, the highest benefits of this method can be derived in the upstream process stages, viz., concept design and development. The quality, cost and time advantages attained in the upfront process activities lead to an overall high quality NPD. This chapter provides an introduction to the concept of Taguchi method (also known as Robust design methodology or simply Robust design) and explores the potential for its application in NPD. The compatibility of TM as an NPD tool are further reiterated in the concluding sections of the chapter.

The chapter is organized around the following main topics:

- Taguchi method - an overview
- The elements of Taguchi method
- Steps in achieving robust design
- Summary of the features of Taguchi method
- The NPRP perspective

4.1 Taguchi Method - An Overview

Taguchi's robust design is an engineering methodology for producing high-quality products quickly and at low cost. Its use can greatly improve an organization's ability to meet market windows, keep development and manufacturing costs low, and deliver high-quality products.

Dr. Genichi Taguchi developed the foundations of the Taguchi method through his research at the Nippon Telecommunications and Telegraph Company (NTT) in Japan in the 1950s, and validated the basic underlying philosophies by applying them in the development of many products. Ever since, this method has been used very successfully in the Japanese manufacturing industry for developing reliable high-quality products at low cost in a wide variety of industries such as the automotive, electronics and process industries. The Taguchi method has been an important factor in the rapid industrial growth and subsequent domination of the international markets in these industries by Japan. As much as 80 percent of the Japanese quality gains have been claimed to be attributable to the Taguchi method [33]. The results achieved in Japan through TM have been incredible. Such has been the extent of implementation of TM in Japan that Nippon Denso alone conducted 2500 case studies in 1985 concerning automotive electrical products [46]. Also, Toyota attributes 50 percent of its success in quality improvement to TM. Within many Japanese companies, training in TM today is considered necessary and a continuing part of every engineer's education. However, TM became known to the rest of the world industry in the mid-eighties. The North American companies were first introduced to Taguchi's methodology in the 1980s through the work done by Dr. Taguchi and his team at the AT&T Bell labs. But, it was the U.S. auto industry and its supplier base who were instrumental in popularising this method. Ford was among the forerunners in implementing TM followed by GM and Chrysler. Since then, the number of companies implementing TM has considerably increased. A few names among these are Xerox, ITT, Flex Technologies, Allen Bradley, The Budd Company, Dana Corporation, Sheller Globe, IBM, GE, Philips, Procter & Gamble, John Deere, Black & Decker, Dupont, Goodyear, Honeywell, Whirlpool Corporation, and McDonnell Douglas. Today, many more companies are implementing TM in the U.S. Since they contain proprietary information, the results of these applications of TM have not always been made public. It is however safely claimed that well over 5000 TM case studies are now completed annually in the U.S. During the past 15 years, American, European and Asian manufacturers have reported a number of successful applications of Taguchi method in reducing process variability, improving product reliability, reducing manufacturing costs and improving process yield [1, 2, 3, 4, 20, 27, 28, 32, 33, 39, 46, 47].

Taguchi method is based on statistical experimental design to provide optimal quality of products and processes. TM is not simply a statistical application of experimental design; rather it is the integration of statistical experiments into the engineering design process. This method adds a new dimension to statistical experimental design by explicitly addressing the following concerns faced by all product and process designers:

- How to economically reduce the variation of a product's function in the customer's environment.
- How to ensure that decisions found to be optimum during laboratory experiments will prove to be so in manufacturing and customer environments.

The answers provided by TM to the two concerns listed above make it a valuable tool for improving the quality, cost and productivity of the product development process. Details of the philosophy and methodology underlying TM are presented in subsequent sections.

4.2 Elements of Taguchi Method

Taguchi method is a quality tool, which helps produce a high-quality product/process cost-effectively in such a way that it delivers *on-target* performance, each time it is used, under all intended operating conditions and throughout its intended life. TM is an excellent tool in the hands of the engineering community of any industry which combines Taguchi's simple yet highly pragmatic, quality philosophy with statistical methods in order to achieve rapid improvements in cost and quality by optimizing product design and manufacturing processes.

The foundation of Taguchi method is based upon two premises:

- Taguchi's Quality Philosophy
- Quality by Design

4.2.1 Taguchi's Quality Philosophy

Taguchi defines the quality of a product as the minimum loss imparted by the product to the society from the time it is shipped [6, 32, 39]. This is the first aspect of Taguchi's Quality philosophy. The second aspect of his philosophy is that, once we are given a target, we should try to be as close to the target as possible because, as we move away from the target, a loss in quality is incurred [6, 32, 39].

Taguchi's *loss to society* definition of product quality is a bit unusual. By *loss* he refers to the following two categories:

- Loss caused by the variability of product-function

- Loss caused by harmful side effects

Taguchi says that the society incurs a loss when the performance of a product is not on target. An example of this would be an automobile breakdown in the middle of the road. The owner will have to spend money on towing and further repairing the vehicle in addition to the time lost and the inconvenience caused. Also, the stalled car might be the cause of traffic jams or accidents. In addition to this, a product might cause loss to the society due to its harmful side effects. Again, in the case of a poor quality automobile, the harmful side effects might be high pollution and noise levels. Taguchi sums this all up as the *loss to society*.

Coming to the second aspect of Taguchi's philosophy regarding *on target* performance, Taguchi's advocates that a product is said to have ideal quality when it delivers on-target performance each time it is used, under all intended operating conditions, and throughout its intended life. This ideal quality serves as a reference point, even though it may not be possible to produce a product with ideal quality. Taguchi emphasizes that this ideal quality level is the one which the manufacturers should strive to deliver to the customer, because the product whose response is on target gives the best performance. As the product response deviates from the target, the quality becomes progressively worse.

This definition of *on-target quality* given by Taguchi is markedly different from the conventional *conformation to specifications* quality approach, in which a product is functionally acceptable if the value of its specified quality characteristic is within a certain specified range of the target response rather than being on target. In this case, all products lying within the specification limits are considered to be good and are accepted, while all those falling outside the specification limits are considered to be bad and are discarded or subjected to salvage operations. Every attempt is made to maintain the product within these limits and no *societal loss* is assumed to occur.

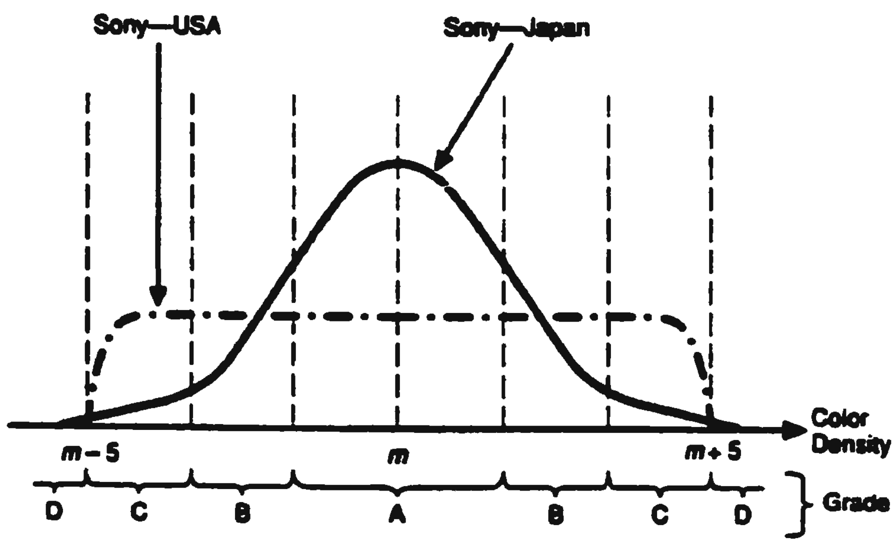
Lets consider the example of a firm manufacturing shafts. The required shaft diameter is 10cm and the specification limits decided on by the engineers are ± 0.002. All shafts within 10± 0.002 cm diameter value are considered to be good, equally good and are accepted; while all the shafts outside these limits are considered to be bad, equally bad and are rejected. The conventional *within specs* concept reasons 'There is nothing wrong if a shaft that should be 10± 0.002 cm in diameter actually comes out to be 9.998 cm.' However, Taguchi argues, 'If a difference of 0.002 cm from target value is acceptable, what on earth suddenly makes a shaft coming in at 9.997 cm viz. 0.003 cm from the target value and only 0.001 cm from the previous value suddenly unacceptable.' Taguchi certainly has a point here. According to him, *there is no abrupt change from perfect to useless as some arbitrary boundary is crossed.* Instead, product performance begins to gradually deteriorate as the quality characteristic deviates from its target value. This deterioration in quality and the *conformation to specifications* issue can be well illustrated with the help of the following example.

In a study conducted among the Sony television users in the U.S., it was found that American consumers showed a preference for the television sets made by Sony-Japan over those made by Sony-USA [6]. The reason cited in the study was quality. Both factories however made televisions using identical designs and tolerances. What could then account for the perceived difference in quality? An investigation into this issue illustrated the distribution of color density for the sets made by the two factories. (Refer Fig. 4.1, p.97).

In the figure, m is the target color density and $m \pm 5$ are the tolerance limits (allowable manufacturing deviations). The Sony-USA factory aimed at producing sets within color density tolerance $m \pm 5$. It produced virtually no sets outside this value. The Sony-Japan factory produced identical sets but it aimed at hitting the target density m, resulting in a roughly normal distribution[1] of densities. Among the sets shipped by Sony-Japan about 0.3 percent were outside the tolerance limits, while Sony-USA shipped virtually no sets outside the tolerance limits. Thus, the difference in customer preference could not be explained in terms of the fraction defective sets (sets lying outside the tolerance limits). Instead, the perceived difference in quality becomes clear when we look closely at the sets that met the tolerance limits. Sets with color density equal to or very near to the target m perform the best and can be classified *grade A*. As the color density deviates from m, the performance becomes progressively worse as indicated in the figure by *grades B and C*. It is clear that Sony-Japan produced many more *grade A* sets and fewer *grade C* sets as compared to Sony-USA. Thus, the average grade of sets produced by

[1] Refer appendix 2 for definition

Sony-Japan was better. As a result, the customer preferred the sets made by Sony-Japan. In short, the difference in the customer's perception of quality was a result of Sony-USA paying attention only to meeting the specifications, whereas, at Sony-Japan the attention was focused on *meeting the target.*



Distribution of color density in television sets

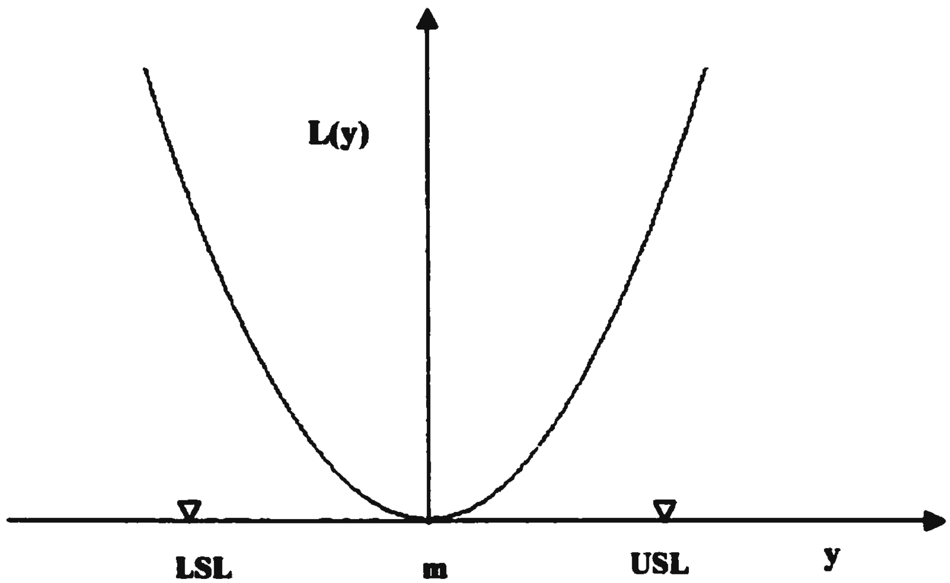
Figure 4.1

In order to evaluate the quality loss incurred each time the product performance deviates from target value, Taguchi infact provides a quadratic function called the Quality loss function abbreviated as QLF. This function evaluates quality loss (loss to society) in monetary terms. QLF is a function of the deviation of a given quality characteristic of a product from its target value. This quality characteristic may be a critical dimension, colour of the product, surface finish or any other characteristics that contributes to the customer's perception of quality.

Mathematically QLF is given by the following equation,

$$L(y) = k\,(y - m)^2$$

where $L(y)$ is the loss in dollars, m is the target or desired value of the quality characteristic, y is the actual value of the characteristic and k is a constant called quality loss coefficient. Fig. 4.2 depicts the QLF graphically.



Taguchi's Quality Loss Function
Fig. 4.2

The graph is a parabolic curve. Values of quality characteristic *y* are plotted against quality loss function *L(y)*. Here *m* represents the target value of the quality characteristic under consideration.

USL and LSL in the figure represent upper and lower specification limits of the quality characteristic, respectively. The QLF curve shows that the total quality loss increases parabolically as the deviation from the target value increases. This loss represents a continuous function. This indicates that making a product within the specification limits does not necessarily mean that the product is of good quality, since good quality is actually keeping the product characteristic on target with low variation.

Taguchi emphasizes that optimum customer satisfaction is achieved by developing products which meet the target value on a consistent basis. Therefore, he rightly states that, when we are given a target, we should try to be as close to the target as possible, rather than being within certain specification limits. The most important aspect of Taguchi's quality control philosophy is, therefore, the minimization of the variation of product performance around the target value.

Taguchi methods strive to produce high quality products at low cost. However, Taguchi's version of a high quality product which conforms exactly to the target would conventionally imply the use of higher-grade material, tighter specifications, higher level of scrap, rework, costly machinery etc.; all necessarily indicating higher product cost. In order to understand how the cost is actually minimized, we first need to briefly explore the elements of product cost.

The three basic elements of product cost are:

- Operating Cost
- Manufacturing Cost
- R&D Cost

4.2.1.1 Operating Cost

The operating cost, which is also called the usage cost, is borne directly by the customer and is directly related to the product's quality. Operating cost consists of the cost needed to operate the product, maintain the product's environment, maintain the product, keep an inventory of spare parts etc. Generally, with TM, this cost can be greatly reduced.

4.2.1.2 Manufacturing Cost

Machinery, raw and semi-finished materials, labor, quality control, scrap, rework etc. all constitute the manufacturing cost. Again, TM helps in lowering the manufacturing cost.

4.2.1.3 R&D Cost

Engineering design, time taken to develop a new product, engineering and laboratory resources, prototype development, field trials etc. constitute the R&D cost of the product. Robust design helps minimize the R&D Cost.

The producer incurs the R&D and manufacturing costs and passes them on to the customer. In addition, the customer also incurs the operating cost.

From Taguchi's philosophy of achieving high quality at low cost, it is evident that there has to be a certain methodology which ensures that the goal of achieving near ideal quality while simultaneously keeping the sum of operator's cost and producer's cost low is achieved.

The next section explains how this elusive goal of high product quality at low cost is achieved.

4.2.2 Quality is a Virtue of Design

Taguchi achieves this goal of high quality at low cost by focussing on the design stage i.e., building quality into the product/process right from the design stage. This concept of *Quality by design* is the second premise of Taguchi methods. Taguchi also refers to this concept of building in quality as *off-line quality control* [6, 39, 46].

There are two stages in off-line quality control:

- Product design stage
- Process design stage

During the product design stage, a new product is developed or an existing product is modified or improved. The goal here is to design a product which is manufacturable and will meet customer requirements. During the process design stage, production and process engineers develop manufacturing processes to meet the specifications developed during the product design stage. Taguchi has developed a three-step approach for designing quality within each of the two stages of off-line quality control. He calls the steps - System Design, Parameter Design and Tolerance Design. These steps are explained in detail in subsequent sections.

4.2.2.1 Product Design Stage

This stage consists of the following steps:

4.2.2.1.1 System Design

In this step, the designer examines a variety of architectures and technologies for achieving the desired function of the product. Initial selection of parts, materials and manufacturing technology is made at this time. Selecting an appropriate mechanism or circuit diagram are examples of system design activity. This is a highly creative step in which the experience and skill of the designer play an important role. Usually, only one architecture or technology is selected based on the judgement of the designer. However, for highly complex products, two or three promising architectures are selected; each one is developed separately, and, in the end, the best architecture is adopted.

4.2.2.1.2 Parameter Design

It is during this stage that the goal of *on-target* functional performance is reached cost-effectively. Before considering the details of parameter design, we will first briefly explore the concept parameters or factors which influence the performance of a product.

A number of factors can influence the performance or response of a product. These factors can be classified as follows:

- Controllable factors
- Noise factors

4.2.2.1.2.1 Controllable factors

These are the factors that can easily be controlled by the design engineer. Examples of controllable factors can be dimensions, materials etc. Each control factor can have multiple values called levels. There are three types of controllable factors: *control factors*, which have a strong effect on reducing the variability of the functional performance around the target; *signal or adjustment factors* which have a strong effect on the mean value of the functional performance but little effect vis-a vis variation; and *cost adjustment factors* which have little effect on either the mean or variability (the cheapest levels of these factors are selected to reduce cost).

4.2.2.1.2.2 Noise factors

These are the factors which are either impossible, difficult or too expensive to control. Taguchi identifies three types of noise factors: *external noise*, or variation in environmental conditions, such as temperature, humidity or supply voltages; *internal noise*, or deterioration such as machinery ageing, product wear etc; and *unit-to unit noise*, which is difference in individual product-units built to the same specifications caused by the inherent variability of the manufacturing process.

Noise factors are responsible for the variation in product performance. For example, a refrigerator's performance (temperature control inside the refrigerator) is affected by noise factors, such as, the number of times the door is opened and closed, variation in ambient temperature, initial temperature of the food, voltage fluctuation (external noise factors), the tightness of the door closure and the amount of refrigerant used (unit-to-unit variation), the leakage of the refrigerant and mechanical wear of compressor parts (internal noise).

The objective of parameter design stage is to determine the levels or settings (*optimum settings*) of the control factors in such a way that the effect of the noise factors on product performance is either reduced or eliminated. Thus, the product is rendered insensitive or *robust* to the variation in noise factors and hence the name *robust design*. Thus parameter design aims at determining the optimum settings of control factors to achieve a robust product in a cost-effective way. It would be pertinent to note here that the uncontrollable factors of variation are not being removed; instead the *effects* of these factors are being suppressed. Details of how to achieve parameter design are given in section 4.3.

Parameter design during the product design stage, reduces sensitivity to all three types of noise factors and thus gives the following benefits:

- The product can be used in a wide range of environmental conditions, so the product's operating cost is lower.
- Lower-grade components and materials can be used.

4.2.2.1.3 Tolerance Design

The tolerance design stage is always the last resort in robust design methodology, and is taken up only if the level of robustness achieved by the parameter design stage is not sufficient. In this stage, the emphasis is on taming the *cause* of the variation. This means going in for tighter specifications, higher-grade materials, precise process-control etc., to achieve the desired quality. A trade-off is made between reduction in quality loss due to performance variation and increase in manufacturing cost. Tolerance design is always an expensive option.

4.2.2.2 Process Design Stage

Like the Product design stage, this stage also consists of the following steps:

4.2.2.2.1 System Design

In this step, the process is selected on the basis of knowledge of the product and current manufacturing technology. The focus here is on building to specification using existing machinery and processes whenever possible.

4.2.2.2.2 Parameter Design

The objective of this stage is to determine the optimum levels for control factors in order to make the process robust, i.e., to minimize the effect of noise factors on the production process and the finished product (process output).

In case of process parameter design, the control factors may be the process setting parameters like machine settings, tool settings etc. The noise factors are: *external noise*, such as ambient temperature/humidity conditions, supply voltages, incoming raw material, operator performance; *internal noise* such as machinery ageing, tool wear; and *unit-to unit noise*, which is the difference in individual product-units built to the same specifications caused by the inherent variability of the manufacturing process. This is also called process nonuniformity. An example of process nonuniformity is found in batch production where many units are processed simultaneously as a batch. For instance, in wave soldering of printed circuit boards, as many as 1000 or more solder joints may be formed simultaneously. Each solder joint experiences different processing conditions based on its position on the board. In some processes, process nonuniformity is an important source of variation.

The parameter design stage in process design, helps achieve a robust process which gives uniformity in the process output, thus reducing unit-to-unit variation. Also, parameter design helps determine optimum process settings that help produce a product with an improved quality level, like better surface finish. In terms of process optimization, parameter design can also be improved to troubleshoot existing product and process problems. The benefits of parameter design in process design can be summed up as follows:

- Wider variation in process conditions can be permitted, thus reducing the need and expense of on-line quality control (process control).
- Raw material can be purchased from many sources and the expense of incoming material inspection can be reduced.
- Less expensive manufacturing equipment can be used.
- The expense and time spent in final inspection on rejects can be reduced greatly.

4.2.2.2.3 Tolerance Design

The tolerance design stage establishes tolerances for the process parameters identified as critical during the parameter design stage. If the product or process design steps are poorly done, it may be necessary here to tighten tolerances or specify higher-cost materials or better equipment, thus driving up manufacturing costs.

4.2.2.3 Quality by Design versus Traditional design

Compared to Taguchi's concept of quality by design, the traditional focus of many manufacturing companies have heavy reliance on tolerance and system design. The parameter design stage is largely ignored.

The traditional design method is also called *functional design*. Functional design ideally creates a prototype process or product that delivers functional performance. This requires research into concepts, technologies and specialized fields, which forms the system or concept design stage. Then, refinements to initial concept design are made through trial and error on the shop floor or through limited field testing of the prototype. True optimization of the design, however, is rarely achieved. No matter how brilliant the concept is, if it is not optimized, it will always lack in quality under actual usage conditions. The deficiency in quality is compensated for by relying on tolerance design and thus *adding on* expensive quality rather than *building it in*. Further, other expensive quality tools like statistical process control and inspection methods are used for assuring quality. All this obviously incurs higher cost, and this cost of quality is then passed on to the customer making the products more expensive.

Thus parameter design is an essential step for getting maximum benefit from any new concept design while making minimum use of tolerance design.

4.3 Steps in Achieving Taguchi's Robust Design (Conducting a robust design experiment)

Since robust design of a product/process is achieved by concentrating on the parameter design stage, let's consider the following steps of Taguchi's approach to parameter design:

- Statement of the problem to be solved
- Selection of the quality characteristic
- Selection of the control and noise factors
- Selection of various levels of the factors
- Designing the experiment
- Conducting the experiment
- Analysis and interpretation of results and determination of the optimum levels of control factors
- Conducting a confirmation experiment

4.3.1 Statement of the Problem (Step 1)

The system (product/process) to be designed, improved or modified is studied and a specific statement of the problem to be investigated is made.

4.3.2 Selection of the Quality Characteristic (Step 2)

A quality characteristic can be defined as that aspect of a particular product/process, which can be taken for the assessment of its quality. The selection of the quality characteristic depends upon the nature of the problem to be solved. Quite obviously, most products will have more than one quality characteristic, and it depends upon the discretion of the engineer to discover which quality characteristic most reflects the performance of the system or is most suitable for evaluating the problem in hand. For instance, while designing a manufacturing process, process yield, processing time and the quality of the process output might be the quality characteristics of interest. More often, the choice of the quality characteristic may depend upon what the customer values most highly. For example, there are different types of cars - sports cars, luxury cars, family cars, available in the market. However, for any type of the car, the buyer wants the automobile to provide reliable transportation. Thus, for a car, the quality characteristic is that it should work each time it is used (on hot summer days or cold winter days) throughout its intended life and should not pollute the atmosphere.

In general the quality characteristics are classified into the following categories:

4.3.2.1 Nominal-the-best

A characteristic with a specific target value. E.g., dimension, volume etc.

4.3.2.2 Smaller-the-better

The ultimate target is the minimum possible. E.g., wear, shrinkage, friction, cost etc.

4.3.2.3 Larger-the-better

The ultimate target is the maximum possible. E.g., strength, life, fuel-efficiency etc.

Single or multiple quality characteristics may be evaluated depending upon the situation.

4.3.3 Selection of Controllable and Noise Factors (Step 3)

After the quality characteristic is selected, all relevant factors that will have an effect (i.e., cause the quality characteristic to deviate from the target) are sought out. These factors are then separated into control and noise factors. As mentioned earlier, control factors are those which can be easily controlled by the design engineer while the noise factors are the ones which are difficult, impossible or too expensive to control. Any existing interactions between the factors are also considered. An interaction between two factors implies that the effect of a factor on the response is affected by some other factor in the experiment.

To illustrate the selection of experimental factors, let's again consider the previous example of an automobile's reliable working (i.e., starting) as the most important quality characteristic. Here, control factors that can be easily manipulated by the designer might include:

- Primary ignition voltage
- Starter speed settings
- Fuel-air delivery system etc.

Noise (or uncontrollable factors) include:

- Outside temperature
- Humidity levels
- Altitude levels at which the engine operates
- Fuel-grades available
- Wearing down of the battery and critical engine parts with the passage of time

It is important to note that the selection of factors is done through a brainstorming session in which people from design, quality, manufacturing and the shop floor participate. An experiment without a thorough brainstorming can lead to unsatisfactory results, since

Taguchi method is all about integrating sound engineering judgement with statistical design.

4.3.4 Selection of Factor-levels (Step 4)

Once the control and noise factors have been identified, multiple settings (levels of operation) for each factor are determined based upon engineering judgement, again through cross-functional brainstorming. Usually, two or three levels are selected and they are taken sufficiently far apart to cover a reasonable range of operating conditions [39]. For example, starter settings might include tuning the engine at three different speeds (i.e., the current speed and two alternatives that might produce better results).

4.3.5 Designing the Experiment (Step 5)

After the factors and their levels have been selected, parameter design requires some form of experimentation in order to study the effect of various factors on the quality characteristic and ultimately determine the factor settings which optimize the quality characteristic.

For this purpose a set of experiments needs to be performed, in which different combinations of factor settings are tested in each experiment. The data from all the experiments is then analyzed to evaluate the effect of various factors on the quality characteristic.

Taguchi uses special matrix experiments called Orthogonal Arrays (OAs) to conduct such experiments. OAs allow the effect of several factors to be determined efficiently, and are an integral part of robust design. The next section deals with OAs in detail.

4.3.5.1 Discussion of Orthogonal Arrays

Conventionally, while searching for an improved design, the engineer identifies the relevant design factors and typically runs some tests, observes the performance of the product and makes a decision whether to use or reject the new design. It is the quality of this decision that can be improved upon when proper test strategies are utilized; in other words, the mistake of using an inferior design or not using an acceptable design can be avoided.

Before discussing OAs, we will briefly mention some commonly used test strategies [48].

4.3.5.1.1 One-factor experiment

The one-factor experiment evaluates the effect of one parameter on the performance while holding all the other factors constant.

4.3.5.1.2 Several factors one at a time

In this case, the effect of several factors is studied by varying one factor at a time while keeping all the others constant.

4.3.5.1.3 Several factors all at the same time

Here several factors are studied while varying them simultaneously.

All these approaches have their limitations. They are not scientifically structured, do not allow the effects of factor interactions to be evaluated, do not make effective use of test data and lack orthogonality (which means the effects of the factors can't be studied independently of each other). These strategies do not lead to an optimum design.

4.3.5.1.4 Full factorial experiment

This is a better approach in terms of orthogonality. Here, all possible combinations of all the factors at their various levels are considered. But this method is very time consuming and expensive as the total number of test trials to be conducted are $(l)^{f}$ (where, f = number of factors, and l = number of levels). Thus, studying 7 factors at 2 levels would require 128 trials. With an increase in the number of factors and levels involved, the number of trials increases progressively.

4.3.5.1.5 Orthogonal Arrays

In contrast to the above test strategies, Taguchi uses more efficient test plans known as Fractional factorial experiments (FFEs) or Orthogonal arrays (OAs). OAs use only a portion of the total possible combination of factors to estimate the main factor effects.

Using OAs significantly reduces the number of experiment configurations and makes it possible to study the effect of a large number of factors using relatively small number of experiments.

Taguchi has developed a family of standard orthogonal arrays, which can be utilized in various situations [6, 39, 46]. An orthogonal array is represented by L_x, where x is the number of trials. Let's consider the example of an L_8 orthogonal array, involving seven, two-level factors as shown in figure 4.3. If a full factorial experiment was conducted, it would take 128 (2^7) experiment trials. An L_8 orthogonal array reduces the number of trials to just 8, which is 1/16th of the total possible trials. The array has a size of 8 rows and 7 columns. The experimental factors to be studied (say A, B, C, D, E, F, and G) are arbitrarily assigned to the vertical columns. The numbers (one/two) in the rows indicate the factor levels. Each row represents an experimental trial.

OAs are constructed in such a way that the vertical columns of these arrays acquire a special combinatorial property: in any pair of columns in an OA, all combinations of the levels (of the two factors assigned to this pair) occur and they do so an equal number of times. For instance, in the L_8 array, if we consider the first two columns to which factors A and B have been assigned, we observe that the two columns together contain all four combinations possible between factor-levels (A_1, A_2) and (B_1, B_2) viz., $A_1 B_1, A_1 B_2,$ $A_2 B_2$ and $A_2 B_1$ and each of these combinations occurs an equal number of times i.e., twice in this case. This is true for every pair of the OA columns. This property is called the *balancing property* or *orthogonality*. Orthogonality permits the use of simple arithmetic to find factor-effects on the response and also helps estimate the effects of individual factors without being influenced by other factors.

	Columns						
Trial no.	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

L_8 Orthogonal Array
Figure 4.3

Taguchi's standard OAs are 18 in all ranging from L_4 to L_{81}. [6, 39, 46]

The following table shows some of the commonly used orthogonal arrays.

Orthogonal Array	Factors and Levels	Total No. of Experiments	Total No. of Experiments (For full factorial)
L_4	3 Factors at 2 levels	4	8
L_8	7 Factors at 2 levels	8	128
L_9	4 Factors at 3 levels	9	81
L_{16}	15 Factors at 2 levels	16	327,678
L_{27}	13 Factors at 3 levels	27	1,594,323
L_{64}	21 Factors at 4 levels	64	4.4×10^{12}

Commonly used Orthogonal Arrays
Table 4.1

As depicted in the above table, a comparison of the reduced number of trials using orthogonal arrays vs. the actual number of trials using full factorial experiments illustrates the real power of OA s in evaluating several factors in a minimum number of experiments, thus saving design cost and time.

4.3.5.1.6 Selection of Orthogonal Arrays

The first step in selecting the correct standard OA involves counting the total degrees of freedom (*dof*) present in the case study. *dof* is a statistical term which gives the number of independent comparisons that can be made within a data set. This *dof* count fixes the minimum number of experiments that must be run to study the factors involved.

In counting the total *dof*, one *dof* is committed to the overall mean. The determination of the rest of the *dof* depends upon the following:

- The number of factors and interactions of interest

- The number of levels for the factors of interest

These two items plus the *dof* for the overall mean determine the total *dof* required for the entire experiment.

The number of *dof* associated with each factor under study equals one less than the number of levels available for that factor. If we have a factor A, with *a* levels then the number of dof ν_A associated with A is given by,

$$\nu_A = a - 1$$

Similarly, for another factor B, with *b* levels, the dof is given by,

$$\nu_B = b - 1$$

The number of *dof* for an interaction is the product of the degrees of freedom of each of the interacting factors.

If there is an interaction between factors A and B, then dof for the interaction is given by,

$$\nu_{AxB} = (\nu_A) \times (\nu_B)$$

The total dof (ν_T) in a give case study are thus determined by the sum of the *dof* of the overall mean and the *dof* for all factors and interactions involved.

ν_T = *dof* (overall mean) + *dof* (all factors) + *dof* (all interactions)

While selecting OAs for a particular case study, the number of rows (or experimental trials) in the OA must be at least equal to the dof of the case study. For example, a case study having four dof could be carried out with a L_4 array. The arrays can be selected from the collection of standard OAs provided in statistical texts. [6, 39, 46]

Once the appropriate OA is selected, the factors and interactions can be assigned to the various columns of the OA.

4.3.6 Conducting the Experiment (Step 6)

Once the experiment is planned, the various trials can be conducted based upon the factor settings in the OA, and suitable data records can be made. The experiment can be conducted in real life or by using mathematical equations or through computer simulation depending upon the situation.

4.3.7 Data Analysis and Interpretation (Step 7)

After the experiment has been conducted, the data obtained needs to be anlayzed in order to select the factor levels which lead to optimized performance of the quality characteristic. Optimized performance means that the quality characteristic gives on target performance with reduced variability around the target. Analysis of variance (ANOVA) on the data helps identify the effect of the various factors on the target mean [6, 36, 39, 46]. ANOVA is a useful statistical technique for determining the relative importance of various factors on the response. In order to determine the variation around the mean, Taguchi gives an objective function called the signal-to-noise (S/N) ratio. S/N ratio measures the variability around the mean. If we literally interpret it, the signal is the target value of the quality characteristic while noise is the undesired effect or variability caused by the noise factors. The emphasis is on maximizing the signal and minimizing the noise, which implies a higher S/N ratio is desirable.

There are three types of S/N ratios depending upon the type of quality characteristic being evaluated:

- For nominal-the-best type of quality characteristic, S/N ratio is given by:

$$S/N = 10 \log_{10} (\mu^2 / \sigma^2)$$

where, $\mu = 1/n \sum_{i=1}^{n} y_i$ and $\sigma^2 = 1/(n-1) \sum_{i=1}^{n} (y_i - \mu)^2$

where, $y_1, y_2, \ldots\ldots\ldots y_n$ are the n observations of the quality characteristic under different replications in a trial.

- For smaller-the-better type of quality characteristic, S/N ratio is given by:

$$S/N = -10 \log_{10} [(1/n) \sum_{i=1}^{n} y_i^{\,2}]$$

- For larger-the-better type of quality characteristic, S/N ratio is given by:

$$S/N = -10 \log_{10} [(1/n) \sum_{i=1}^{n} 1/y_i^{\,2}]$$

Whatever the type of quality characteristic, the S/N ratio, is always interpreted in the same way: the larger the S/N ratio, the better it is.

Having computed the S/N ratios for each trial, they can further be analyzed by using ANOVA to determine the significant factors affecting the variability. This has become a standard practice, although Taguchi himself does not consider it necessary. He argues that the S/N ratios are competent enough to highlight the significant factors and do not need to be analyzed through ANOVA. Instead he suggests a simpler graphical approach in which the average values of the S/N ratios for each level of a particular factor are plotted against the factor-levels themselves. These plots are called average plots, and the significant factors and their optimum levels are visually interpreted.

The results of the data analysis are interpreted to determine which factors are influential and which are not pertaining to the quality characteristic. The following information is derived about the factors:

- Factors which affect both mean and variation Class 1
- Factors which affect variation only Class 2
- Factors which affect mean only Class 3
- Factors which affect nothing Class 4

Class 1 and Class 2 are the control factors, Class 3 are adjustment factors whereas Class 4 are cost adjustment factors as have already been discussed in section 4.4.2 under *Parameter design*. Optimum levels of the factors which give the desired quality characteristic are then selected. The details of the data analysis and the underlying theory will be covered in the case study in Chapter 5.

4.3.8 Confirmation of the Experiment (Step 8)

A confirmatory run/experiment should be carried out to confirm the optimum settings obtained. If conclusive results are obtained, then the optimum settings are confirmed. They can now be used for achieving the required improvements in the system. However, if the results do not turn out as expected, further investigation may be required [some important factors (s) may have been left out of the experiment and more screening might be needed, which implies returning to step # 3 and conducting the experiment again].

Thus, all these steps lead to a complete robust design experiment.

4.4 Summary of the Features of Taguchi Method

The features of Taguchi method can be summarized as follows:

- Upstream focus
- Cross-functional focus
- Flexibility
- High quality at low cost

4.4.1 Upstream Focus

Taguchi method advocates building quality products by focussing on product and process design in the upstream stages of R & D. A major part of R & D is involved in producing drawings, specifications, concepts and other relevant information needed to manufacture products that meet customer requirements. Knowledge of scientific phenomenon and past engineering experience with similar product designs and manufacturing processes forms the basis of the engineering design activity. However, in case of new products, a number of new decisions related to the product must be made regarding product architecture, parameters of product design, the process architecture, and parameters of the manufacturing process. Conventionally, a large amount of engineering effort is consumed in conducting experiments (either with hardware or by simulation) to generate the information needed to guide these decisions. Efficiency and accuracy in generating such information is the key to meeting market windows, keeping development and manufacturing and development costs low, and having high-quality products. TM provides an engineering methodology for improving productivity during research and development, so that high-quality products can be produced quickly at low cost. TM uses orthogonal arrays to study a large number of decision variables with small number of experiments for obtaining dependable information for making engineering decisions. Thus, TM provides total upstream focus for new product development by designing robust products and processes (therefore reducing the need for more expensive downstream quality-activities) and by accelerating the R & D stage.

4.4.2 Cross-functional Focus

The Taguchi philosophy professes that the task of assuring quality must begin with the engineering of quality, i.e., by product and process design optimization for performance quality and cost. To be effective, it must be a team effort involving *marketing, design* and *manufacturing*. Thus, TM endorses the CE philosophy of cross-functional teamwork.

4.4.3 Flexibility

Though TM is primarily an upstream quality tool, it is still flexible enough to be implemented as a problem-solving tool throughout the whole product development process.

4.4.4 High Quality at Low Cost

High quality at low cost is inevitably the quintessential element of Taguchi method. The whole ideology of TM is aimed at achieving this very coveted goal.

4.5 The NPRP perspective

All the features of Taguchi method discussed in section 4.4 make it a highly compatible tool for the NPRP model, which itself emphasizes on upstream focus, cross-functional teamwork, accelerated product development times, high quality and low cost.

Also, continuing with our focus on upstream activities in NPD, we will evaluate the potential of TM in the concept design stage to optimize the *Rapid prototyping process*. Rapid prototyping (RP) is yet another NPD tool, which helps produce quick prototype models of product concepts and thus aids in improving the accuracy and efficiency of R&D decisions, ultimately leading to high quality products with shorter development cycle times.

If the RP process is further optimized through the application of TM, it will result in enhanced efficiency of the product and process design activities. This will further improve the efficacy of the upstream stages of the NPRP model, hence making it more effective. In the next chapter, we briefly review Rapid prototyping, and we explore the possibility of applying Taguchi method for optimising the Rapid prototyping process.

Chapter 5

5. Application of Taguchi Method in Rapid Prototyping Process Optimization

Reiterating the focus of the NPRP model on upstream activities in NPD, this chapter endeavors to evaluate the potential of Taguchi method (as a front-end NPRP tool) in the concept design stage, in the context of Rapid prototyping (RP); where RP is yet another NPD tool used for producing quick prototypes of product concepts.

A case study in RP featuring the Laminated Object Manufacturing (LOM) process, which is one of the popular RP processes, has been discussed in this chapter for demonstrating the potential of TM as a front-end NPRP tool for achieving high quality, low cost and accelerated NPD.

The study was conducted at the Manufacturing Technology Centre (MTC), a part of the Industrial Outreach Group (within the Faculty of Engineering and Applied Science at MUN), which caters to the production of rapid prototypes for the provincial industrial clients. Considering the availability of in-house facilities already involved in industrial prototyping, it was decided to conduct the case study in-house, in order to optimize the existing LOM process, currently in use at MTC for building rapid prototypes of industrial products.

The chapter introduces the concept of Rapid prototyping (RP), and the LOM case study is then presented.

The chapter is organized around the following main topics:

- Introduction to Rapid prototyping technology
- Benefits of RP in NPD
- Laminated Object Manufacturing
- LOM process optimization – a Case study

5.1 Rapid Prototyping Technology – An Overview

Rapid prototyping is a time-compression technology tool relevant to NPD. A concise overview of the RP process is provided in the initial sections of the chapter in order to apprise the reader with the concepts underlying RP. This is furnished with a view to facilitate better understanding of the RP process optimization case study (using Taguchi method) which is the major focus of this chapter. An exhaustive discussion of the RP technology is beyond the scope of this thesis.

Rapid prototyping is one of the names given to a technology which converts designs from computer representations directly into solid objects. Solid physical models of parts are made directly form 3D CAD model data without any special tooling. The technology is also known as Solid free-form fabrication, Desktop manufacturing, Tool-less manufacturing or Layered manufacturing.

Within a rapid prototyping process, the object is first designed using a CAD system (usually a 3D solid modeler like I-DEAS, CATIA, Pro/Engineer etc.). The CAD model is an essential prerequisite in RP. The CAD data is then converted into a special format called the .STL format. (In simple terms the .STL format uses triangular facets to approximate the surface of the 3D design model.) The data is then sliced into thin (~ 0.005 inches) cross-sectional planes by the computer. The cross-sections are sent from the computer to the RP machine, which builds the part layer-by-layer. The first layer's geometry is defined by the shape of the first cross-sectional layer generated by the computer. It is bonded to a platform or starting base, and additional layers are bonded on top of the first, shaped according to their respective cross-sectional planes. The process is repeated until the prototype part is completely built.

Taking a brief look at the Rapid prototyping history, RP first appeared as a commercial technology in 1988. Since then, several distinct RP technologies have emerged. These technologies differ from each other in terms of materials used and build techniques. The following is a brief listing of some of the popular RP technologies currently in use.

5.1.1 Stereolithography (STL)

This is the foremost of RP techniques, developed by 3D Systems Inc. in 1986. The Stereolithography based RP system known as Stereolithography Apparatus (SLA) first became commercially available in 1988. Using the .STL file in a personal computer-like control system, the SLA builds physical models one layer at a time. After slicing the data into thin cross-sections, a UV laser traces each successive cross-section of the object onto the surface of a vat filled with a liquid photopolymer. The liquid photopolymer hardens only where touched by the laser beam. As it does, the model is lowered in the vat of liquid so that a new liquid layer spreads over the solidified layer. Then, the next contour is drawn by the laser. The process repeats until the part is complete. A post-curing heat process is often required to completely harden the model. Finishing is performed if needed to create smooth surfaces on the model.

5.1.2 Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM), developed by Stratasys Inc., uses thermoplastic wire-like filaments which are melted in the material deposition head. The material is then extruded from the head and deposited on a layer-by-layer basis. The XY controlled extrusion head traces out the CAD information for each layer. As one layer solidifies, the next layer is deposited and the model is built upwards. The materials used are ABS plastic, medical grade ABS plastic and investment casting wax.

5.1.3 Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS), from DTM Corporation, traces the shape of the part to be modeled in a thin layer of powder. The laser sinters the powder together. After the laser passes, the platform lowers, another layer of powder is deposited and the laser traces the pattern of the corresponding cross-section. After all the layers have been formed, the finished part is embedded in a cake of loose powder, which is later removed. Materials used for SLS include polycarbonate, investment wax, nylon and ABS.

5.1.4 Solid Ground Curing (SGC)

Solid Ground Curing (SGC), from Cubital Ltd., uses large machines known as Soliders to expose design layers to photopolymer. Resin is removed from unexposed regions and replaced by wax which supports the growing model. The wax is removed after all the layers have been made.

5.1.5 Three Dimensional Printing (3DP)

Three Dimensional Printing (3DP) is a process under development at MIT for the rapid and flexible production of prototype parts, end-use parts, and tools directly from a CAD model. Parts are constructed by selectively applying binder to thin layers of powdered material, causing the particles of the powder to stick together. Each layer is formed by generating a thin coating of powder and then applying binder to it with an inkjet-like mechanism. Layers are formed sequentially and adhere to one another to generate a 3D object. Several materials, including ceramics, metals, polymers and composites can be used for fabrication.

5.1.6 Direct Shell Production Casting (DSP)

Direct Shell Production Casting (DSP), from Soligen Inc., fabricates molds with integrated cores from a CAD design with no intervening steps. It sinters ceramic powder layers on a descending platform with a piezo-electric inkjet head.

5.1.7 3D Printing and Deposition Milling

Sanders Prototype have developed 3D Printing and Deposition Milling which also uses piezo-electric inkjet heads to deposit thermoplastic model material and wax support material. Two jets are used: one for the thermoplastic and one for wax. Each layer is milled to a desired thickness. The process produces ultra-smooth surface finishes.

5.1.8 Ballistic Particle Manufacturing (BMP)

Ballistic Particle Manufacturing (BPM), from BPM Inc., of Greenville, South Carolina, jets micro-particles of molten thermoplastic from a piezoelectric nozzle to a defined location. As the particles harden, they build the model upward, particle by particle. The desk-side unit uses a five-axis, robotic head to position the nozzle.

5.1.9 Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing (LOM), from Helisys Inc., cuts rolls of adhesive coated paper to build a model. The paper is rolled over the target area from a supply roll to a take-up roll. After a laser cuts the design layer into the paper, the paper is indexed, bonded to the previous layers, and cut. The automatic process continues until all layers are cut. The model is then removed from the surrounding material. More details of the LOM process will be taken in section 5.3.

The costs of the RP systems vary, as does maintenance and modeling materials. Each system has its advantages in terms of surface finish, accuracy, part-size rigidity, build-time etc. Therefore, RP systems should be selected depending upon their suitability for specific applications.

5.2 Applications of Rapid prototyping

Rapid Prototyping techniques allow quick production of physical prototypes in a cost-effective manner. In the manufacturing sector, Rapid prototyping finds its applications in a wide range of industries including aerospace, automotive, consumer products and medical. It is well suited to prototype components and products as diverse as aircraft propeller blades, knee implants and intake manifolds.

The various applications of Rapid Prototyping are discussed as follows.

5.2.1 Visualization

The rapid prototype of a part offers improved visualization as compared to reading blueprints or CAD images, especially if the part design is complex. Improved visualization not only provides better insight into the product design, but also facilitates the detection of any design errors or overlooked features. Also, in case of new products, the design concepts translated into actual tangible forms through RP, facilitate better interpretation and communication of the product idea among the development team, suppliers as well as customers.

5.2.2 Verification

RP technology facilitates the verification and validation of product design. Conventionally, generating a fully comprehensive series of prototypes to prove the validity of design often involves spending more time and money than is available. Sometimes errors are overlooked in order to meet the time and budget constraints. This compromise results in poor product quality. In contrast, an RP prototype can be generated so quickly that it becomes simple to verify the design through a series of iterative prototypes, if required, and finally achieve a validated design. This applies mainly to geometrical verification of the product features. Obviously, verification of other characteristics, such as, strength, operational temperature limits, fatigue, corrosion resistance, etc., have to wait for the test results on a fully functional prototype. However, since the part is geometrically verified much earlier, this speeds up the building of the functional prototype. In some cases, it is possible to directly fabricate functional prototypes using certain RP technologies. Fabrication is done either by using a material with appropriate properties in the RP process itself, or by using the prototype as a pattern or mold for a subsequent process. On-going research is aimed at direct manufacture of functional parts through the RP process and further improvements in this field. Thus, rapid prototypes allow the verification of design in terms of form, fit and functionality depending upon the nature of the prototype, i.e., whether it is fully functional or visual. The design verification is applicable to concept design as well as later design verification stages.

5.2.3 Design Optimization

Design optimization, usually done via statistical experimental design, requires a number of test models to be fabricated. RP facilitates quick and economical production of these test models within weeks, which otherwise would take a substantially longer time to manufacture. Thus, RP helps in achieving an optimized design at an accelerated pace. This is applicable to both product and process design optimization.

5.2.4 Rapid Tooling

The concept of rapid prototyping has been extended to produce tough production tooling. New materials and better RP processes are letting rapid-prototype machines fabricate tooling that is good enough to produce parts with tolerances, surface finish and properties of an actual finished product.

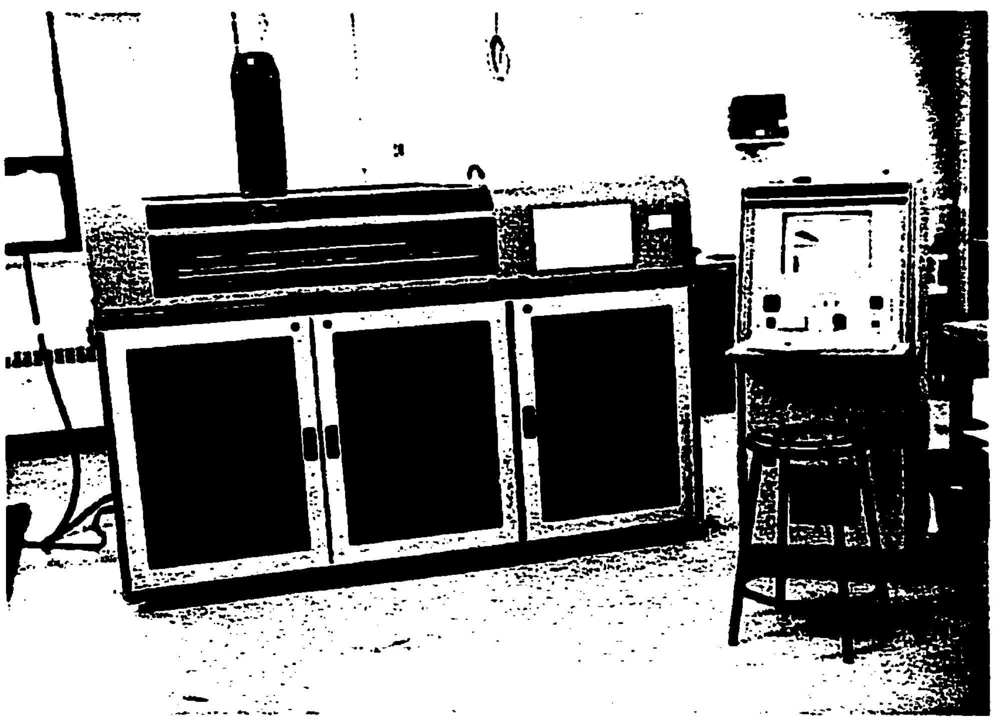
All these applications of Rapid Prototyping make it an excellent technology tool for the new product development process. With the various features that it offers, RP facilitates idea-visualization, concept development and testing, design optimization, design verification/validation and concurrent product development in an accelerated and cost-effective manner. This helps achieve economic, accelerated and quality NPD.

5.3 Laminated Object Manufacturing

In this section, we will discuss Laminated object manufacturing in detail, in order to facilitate better understanding of the case study (featuring the LOM process) discussed later in the chapter.

5.3.1 LOM-2030E (System Overview)

LOM-2030E, from Helisys Inc. (shown in Fig. 5.1), is the LOM System featured in the study.



LOM-2030E System
Fig. 5.1

The following provides a brief overview of LOM-2030E

5.3.1.1 Hardware

The LOM-2030E System (Fig. 5.1) consists of a control console (with a standard control computer), a cabinet (with canopy), a laser cutting system, a paper feed system, a lamination system, and a Z-table system.

5.3.1.1.1 Control Console

The control console is a stand-alone unit that is connected via cables to the LOM-2030E cabinet. The console contains the control computer system, the control panel and the laser chiller unit. The control computer is used to control the LOM-2030E and pre-process the CAD files. Since the LOM-2030E uses a laser system, a laser chiller unit is required to cool the laser system with recirculated water. The chiller is located in the bottom of the control console.

5.3.1.1.2 Cabinet

The cabinet and its canopy encloses the remainder of the LOM-2030E System, except for the rewind assembly. The cabinet has numerous doors, allowing easy access to various mechanisms inside.

5.3.1.1.3 Laser Cutting System

LOM-2030E uses a 50 watt CO_2 laser. The laser cutting system consists of the laser mechanism and the XY positioning system that contains the beam focusing optics via which the final laser beam is delivered to the cutting surface.

5.3.1.1.4 Paper Feed System

The paper feed system has a paper feed assembly (located inside the LOM cabinet) and a rewind assembly. The paper feed assembly feeds the paper through to the machine and keeps it taut throughout the building process. The rewind assembly is an external roller that collects the waste paper and is located external to the LOM cabinet.

5.3.1.1.5 Lamination System

The lamination system uses heat and pressure to bond each new layer of paper to the *just-cut* layer. The system basically consists of a fuser (also called the heater) and two limit switches. The fuser is a heated roller which moves from right- to-left over the new layer of adhesive paper. When the fuser rolls over the paper layer, it performs three functions. It heats the adhesive on the new layer, causing it to become tacky; applies pressure to both the new and the *just-cut* layer causing them to bond and pushes out all the air bubbles between the two layers. The limit switches protect the fuser from moving too far to the left or right within the machine.

5.3.1.1.6 Z -Table System

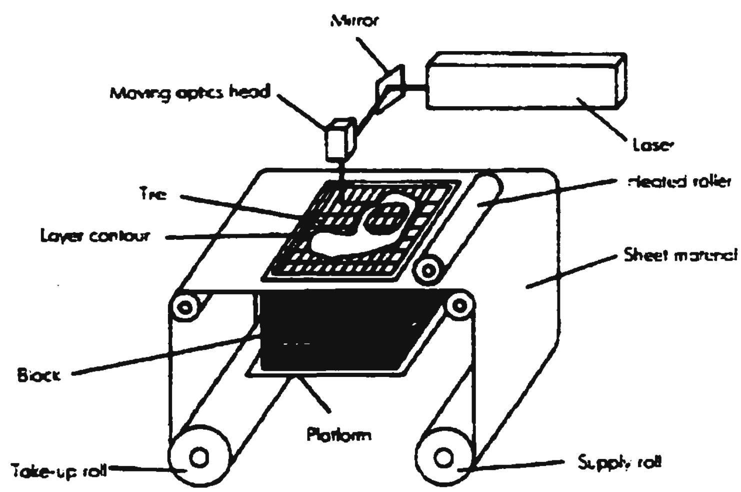
The Z-table system is an elevator-like unit that functions as the platform for building the part. As the LOM machine builds a part, the Z-table moves down for each layer. A limit switch prevents the Z- table from moving too high or too low within the machine.

5.3.1.2 Software

The LOM-2030E's software consists of Helisys' LOMSlice software which runs on MS Windows NT, version 3.5. LOMSlice is a user friendly, menu driven program which imports and processes CAD .STL files, generates three-dimensional prototype parts using processed .STL files, and controls and monitors the LOM-2030E hardware. LOMSlice accepts files in .STL format. Solid modeling CAD packages like I-DEAS, AutoCAD, CATIA, etc., can be used for creating .STL files.

5.3.2 LOM-2030E Part Building Process

The CAD .STL file of the required part is imported on to the control computer of the LOM machine and processed by LOMSlice. Part building is then initiated on the machine. The simplified configuration of the machine depicted in Fig. 5.2 (p.143) helps better visualize the part building process.



Configuration of the LOM machine depicting the part building process

Figure 5.2

Paper is supplied from a roll on the feeder assembly and waste paper is collected by the rewind assembly. The part is fabricated on the part platform (on the Z-table system). The laser beam, delivered through the beam focussing optics mounted on the XY positioners, cuts the appropriate contours of the part on the paper, and the part is built layer by layer. Areas of each layer not included in the part contours are then cut into small pieces called crosshatches or tiles. Cutting crosshatches makes it easier to separate the part from the waste material after the part has been built. The entire surface of the material is coated with adhesive, therefore each layer adheres to the previous layer. The requisite heat and pressure required for adhesion is provided by the fuser, the heated roller located above the paper. After the contours of the part have been cut on one layer, the platform drops down to make room for another layer of paper. The fuser then applies heat and compression to bind the new layer to the previous one. The contours are now cut on the new layer, and this process continues till the whole part is built. After all the layers have been laminated and cut, the result is a part embedded within a block of supporting material. The material is then broken loose into chunks along the crosshatch cuts, revealing the required part. The part is finally sanded and lacquered to obtain a good surface finish.

5.3.3 Part Building Material

The part building material is a special high strength adhesive-coated LOM paper. Following paper grades are available. (Trade names are given.)

LPH 042, Paper thickness = 0.0042" (0.107mm)

LPH 082, Paper thickness = 0.0082" (0.200 mm)

LPS 038, Paper thickness = 0.0038" (0.097 mm)

5.4 Case Study featuring LOM

In recent years, a few case studies have been conducted to optimize the SL process in RP [27, 28, 48], using Taguchi method and DOE. But, literature does not show any reference to Taguchi optimization studies of the LOM process and this is the first study of its kind in this field. A possible reason for this could be that SL, being the first ever RP technique to become commercially available, is probably the most commonly used in the industry and has generated more research interest. Also, dimensional accuracy has been more of a problem in SL as compared to other RP techniques, which might have lead to the part optimization studies in SL. Probably, the other factor responsible for an overall scarcity of literature in RP process optimization is the non-availability of industrial case studies due to proprietary reasons.

This section presents a study on LOM process optimization (featuring LOM-2030E), with a view to investigate the potential of Taguchi method as a LOM process optimization tool. As mentioned earlier, the case study was conducted at the Manufacturing Technology Center (MTC), Faculty of Engineering and Applied Science, MUN.

5.4.1 Background and Objectives of the Case Study

In order to gain deeper insight into the LOM process and identify possible process optimization areas, several brainstorming sessions were conducted with the MTC personnel involved in the process.

The basic objective of the study was to optimize the LOM process in order to obtain improved part quality and process efficiency. At the time, in terms of part quality, dimensional accuracy was not a problem since the LOM machine delivers fairly accurate parts.

However, the other important criterion that defines the quality of parts is the quality of paper lamination achieved. This was the area that seemed to have problems. As mentioned before, different grades of paper (LPH 042, LPH 080 and LPS 038) can be used for part manufacture. At MTC, the paper grades currently in use are LPH 042 and LPH 080. For our research, we decided to build parts using the LPH 042 paper.

The manufacturing experience so far showed that the lamination quality is poor when in-process part temperature exceeds 120° F (48.89° C). The layers of paper do not bond properly, which ultimately affects the part quality and results in scrap.

Process settings yielding reasonably good part quality had been achieved at MTC, but the process had to be monitored at times, in case the part temperature exceeded 120° F, and the parameters had to be reset. Otherwise, the part quality was compromised. So, it was desired that the maximum in-process part temperature stay at or below 120° F (within 118° F - 120° F) without any resetting as this would yield good quality parts.

Also, unlike mass production, RP is marked by requests for new parts with each order. Even though there are sometimes repeat orders, building new parts each time is the general norm. This aspect of RP raised another issue. The process settings vary with each part depending upon its geometry and complexity. This requires considerable trial and error for each part before the desired settings are obtained. The process is not standardized and relies heavily on the expertise of the LOM operator.

Another possible aspect of the process that could be optimized was the part build time. This issue had not been addressed before and was not considered to be as significant as the in-process part temperature. But, as an efficient process is always characterized by the minimum processing time, part build time appeared to be the other potential process criterion that could be optimized.

Considering the above background information on the existing LOM process, the objectives of the study were outlined as follows:

- To conduct a screening experiment in order to investigate the effect of various parameters on LOM process optimization and hence determine the potential of Taguchi method as a LOM process optimization tool
- To achieve a maximum in-process part temperature of 120° F
- To reduce the part build-time to the minimum possible
- To reduce the process variability (in terms of part temperature) from trial to trial for similar parts and extend the setting to different parts in order to make the process more generic

All these objectives would essentially lead to an efficient LOM process with high part quality, lesser build-time, reduced costs (by lowering the amount of scrap and the number of build iterations) and more process standardization.

5.4.2 Experimental Strategy

Since the basic objectives of the study comprised conducting a screening experiment to identify the main factors that affected the LOM process (in terms of achieving a maximum in-process part temperature of 120° F and minimum build time) and then finding the optimum settings for these factors, it was decided to achieve these objectives for a particular test part, at first.

Since each incoming part is unique in terms of its features, it is hard to define a test part that would ideally represent all the features of a part to be manufactured. Broadly, a part can be classified in terms of size, shape and complexity. To keep things simple for the experiment, it was decided to choose an average sized test part from the existing sample of already manufactured parts. A shoe sole (Fig. 5.3), with the three basic dimensions of length (l) = 210 mm, width (w) = 77.60 mm and height (h) = 31.30 mm, represented a fairly average sized part with moderate complexity. For the shoe-sole, a part block of approximately (210 mm) x (77.60 mm) x (31.10 mm) would be manufactured on the LOM machine. (Drawings of the Shoe-sole depicting major dimensions are given in Appendix 4).

Sole Bottom

Sole Top

Shoe-Sole
Figure 5.3

Thus, the shoe-sole was chosen as the test part. It was decided that a screening experiment would be conducted on the test part, in order to study the effect of various factors on the LOM process and identify the major factors. The process would then be optimized for the test part and the settings extended to similar parts belonging to the same part family. Finally, the settings would be tested on other parts in order to explore the feasibility of making the process more generic.

5.4.3 Quality Characteristics to be Measured

One of the quality characteristics to be measured was the maximum in-process part temperature, since it affected the part quality. The part temperature is automatically measured by the built-in sensors in the LOM machine and recorded in a log file generated by LOMSlice. The log file maintains a record of the activities taking place during the part building process.

The other quality characteristic or response to be measured was the part build-time, i.e., the total time taken by the machine to build the part. The part build-time is also displayed in the log file after manufacturing is finished.

Thus, there were two responses to be measured during the experiment;

- Maximum in-process part temperature
- Part build-time

5.4.4 Identification of Factors affecting the Experiment

After discussions with the MTC personnel, the following variables were identified as the factors that affected the LOM process. Prior experience in LOM operation and the literature provided by the manufacturer (Helisys' System/Users' manuals) were the major sources of information in deciding upon the relevant factors.

5.4.4.1 Control Factors and their Levels

The initial control factors were identified as follows:

- Heater Temperature
- Heater Speed
- Compression
- Cutting Speed
- Laser Power
- Crosshatch Size

Heater temperature is the temperature of the fuser (heater). As discussed earlier in the chapter, heat is transferred from the fuser to the paper (part-building material) in order to melt the adhesive for bonding of the paper layers while building the part. This parameter is set using the Temperature control on the Control console. *Heater speed* defines how fast the Fuser rolls over the paper during bonding. The faster the Fuser moves, the less is the heat that is transferred to the paper. *Compression* is the amount of pressure applied to the part by the Fuser. It is factory set at a value of 0.762 mm and is held constant. Since compression is a control parameter with a pre-defined value at a constant setting, it was filtered out of the list of control parameters which were to be tested for different settings. *Cutting speed* defines how fast the laser moves while cutting the layers of paper. *Laser power* is the amount of laser power that is made available for cutting. A RP part is built within a solid block to support the part during the building process. *Crosshatches* are small square cross-sections that are cut around the exterior of the part in order to facilitate the separation of the part from the extraneous material around it.

Finally, five control factors at two levels were considered for the experiment. These factors and their levels used for the study are shown in Table 5.1, (p.153).

Factor	Levels	
	1	2
A. Heater Speed	1.5 ips (38 mm/s)	3.0 ips (76 mm/s)
B. Heater Temperature	320° F (160 C)	340° F (171 C)
C. Cutting Speed	14 ips (356 mm/s)	18 ips (457 mm/s)
D. Laser Power	12.5 W	18 W
E. Crosshatch Size	0.05" (12.7 mm)	1" (25.4 mm)

Control Factors and their Levels
Table 5.1

ips [1]= inches/second

The levels chosen for the control factors were decided based upon the range of parameter settings recommended in the System manual and prior manufacturing experience.

5.4.4.2 Noise Factors

In this case, the possible noise factors could have been the ambient temperature and the paper quality. The ambient temperature, which influences the operating environment of the LOM machine, is required to be within 10 to 27° C (50° F - 80° F). The paper quality requires temperatures in the same range for storage purposes, as the adhesive quality

[1] Since the standard unit system used by the LOM machine is FPS, and it is also the system being used at MTC for LOM m/c operation, the same system has been used for the study. However, corresponding conversions are given in SI units.

deteriorates otherwise. Since local temperature conditions stay approximately within required levels, both of these noise factors were ruled out. The possible noise could then be attributed to the natural variability of the process. Thus, the major emphasis of the experiment was now to find optimum settings for the process by concentrating on the control factors.

5.4.5 Selection of the Orthogonal Array

The standard methods of selecting Orthogonal arrays, described in Chapter 4 (section 4.3), were used to select an OA suitable for the case study.

The first step while selecting an OA is to determine the total degrees of freedom (*dof*), ν_T. associated with the study.

ν_T = *dof* (overall mean) + *dof* (all factors) + *dof* (all interactions)

dof for overall mean = 1

dof for a factor with x levels is: $\nu_x = x - 1$.

The *d.o.f.* associated with each of the control factors A,B,C,D,E, viz., heater speed, heater temperature, cutting speed, laser power and crosshatch size respectively, were calculated

The *dof* associated with the factor A was given by: $\nu_A = 2\text{-}1 = 1$

Similarly, the *dof* for the rest of the factors were: $v_B = 1$, $v_C = 1$, $v_D = 1$, $v_E = 1$

dof for the interaction AxB: $v_{AxB} = (v_A) \times (v_B) = 1$,

$\therefore\ v_T = 1 + 5 + 1 = 7$

Thus, the total degrees of freedom associated with the case study were 7, and at least seven experimental trials were required to find the optimum settings. For conducting the study, an OA, which allowed 5 factors and one interaction to be explored at 2 levels, using at least 7 experimental trials, was required. Standard OA L_8 (Fig. 5.4) was selected, as it allowed the exploration of a maximum of 7 factors at 2 levels each, in 8 trials.

	Columns						
Trial no.	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

L_8 Orthogonal Array
Figure 5.4

5.4.6 Assigning Factors to the Orthogonal Array

- Factors were assigned to the various columns in the OA according to the interaction table and linear graphs provided by Taguchi for the L_8 array [6, 39, 46]. The first two columns were assigned factors A and B respectively. According to the interaction table, column 3 would estimate the interaction of the factors in columns 1 and 2. Therefore, the interaction AxB was assigned to column 3. Since there were no more interactions to be estimated, the rest of the factors could be assigned to the remaining columns at random. Thus, columns, 4, 5, 6, were assigned factors C, D, and E respectively. Since all the factors and interactions had now been assigned, column 7 was left empty. It is acceptable to leave column(s) empty in an OA. The empty columns are be used for the estimation of experimental error *e*. Error includes all experimental error, including the measurement error and the error due to uncontrolled factors. Table. 5.2 shows the L_8 array with all of the assigned factors.

Trial #	Columns						
	1	2	3	4	5	6	7
	A	B	AxB	C	D	E	e
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

L_8 Orthogonal Array with assigned Factors
Table 5.2

5.4.7 Conducting the Experiment

The experiment was finally conducted using the shoe as the test part. Eight trials were carried out. Two replications were performed for each trial. The order of the trials was randomized.

The two required responses, viz., *maximum in-process part temperature* and *part build-time* were measured for each trial. The experimental data recorded in the trial sheets is shown in Table 5.3.

Trial order		Response			
Standard	Random	Part Temperature (°F)		Part Build-Time (Hrs.)	
		Replication #		Replication #	
		1	2	1	2
1	1	118.00	119.55	9.08	9.10
2	7	118.84	121.29	7.22	7.17
3	2	122.40	121.75	7.10	7.11
4	6	114.49	116.07	8.53	8.43
5	8	114.78	113.93	6.57	6.47
6	4	121.67	122.01	6.54	6.49
7	3	122.13	121.95	6.53	6.59
8	5	116.84	118.34	8.28	8.34

Response data
Table 5.3

5.4.8 Data Analysis

The analysis of the observed response data was conducted as follows:

5.4.8.1 Step 1

The first step in data analysis was to calculate the S/N ratio and mean response for the data set of each experimental trial. MINITAB R 12 was used for calculation purposes.

5.4.8.1.1 Calculations for part-temperature data:

Since the main objective was to maintain the maximum in-process part temperature on target i.e., at 120° F, and reduce the temperature variation, *nominal-the-best* type of S/N ratio was employed.

Nominal-the-best type of S/N ratio is given by,

$$S/N = 10 \log_{10} (\mu^2 / \sigma^2)$$

where, $\mu = 1/n \sum_{i=1}^{n} y_i$ is the mean response

and $\sigma^2 = 1/(n-1) \sum_{i=1}^{n} (y_i - \mu)^2$ is the standard deviation where, y_1, y_2,............. y_n are the *n* observations of the response under different replications in a trial.

The following table displays the S/N ratios, mean values and standard deviations calculated for the part temperature data.

Trial #	Part Temperature Replication #		Mean (μ)	Std. Deviation (σ^2)	S/N ratio
	1	2			
1	118.00	119.55	118.775	1.09602	40.6982
2	118.84	121.29	122.075	0.45962	48.4846
3	122.40	121.75	122.040	0.12728	56.6394
4	114.49	116.07	121.840	0.24042	54.0965
5	114.78	113.93	117.590	1.06066	40.8959
6	121.67	122.01	115.360	1.23037	39.4404
7	122.13	121.95	120.065	1.73241	36.8153
8	116.84	118.34	115.370	0.83439	42.8145

Calculated parameters for Maximum in-process Part temperature
Table 5.4

5.4.8.1.2 Calculations for part build-time data

In case of part build-time, reducing the time required to build the part was the main concern, rather than reducing the variation in time. Hence, it just required an adjustment factor to reduce the mean value to the minimum possible. S/N calculations were not required.

The following table depicts the mean value calculations for part build-time.

Trial #	Part build-time (hrs.) Replication #		Mean (μ)
	1	2	
1	9.08	9.10	9.090
2	7.22	7.17	7.195
3	7.10	7.11	7.105
4	8.53	8.43	8.480
5	6.57	6.47	6.520
6	6.54	6.49	6.515
7	6.53	6.59	6.560
8	8.28	8.34	8.310

Mean values for Part build-time
Table 5.5

5.4.8.2 Step 2

The next step in data analysis was to analyze the S/N ratios and mean response values in order to identify the significant factors. Taguchi suggests a simple graphical approach using average plots of S/N ratios and mean response values for this purpose, while the other approach is to use the statistical analysis of variance (ANOVA). Although according to Taguchi, average plots are sufficient to make the necessary inferences and they are also much simpler, it has become a standard practice to use ANOVA as well. ANOVA can be used as a tool to compare and reconfirm the results obtained from average plots. Many case studies in the literature use both approaches [1,2,3,4,5,6,8,20,28,32,39]. In the present study, both the approaches have also been used.

The salient details pertinent to data analysis using average plots and ANOVA are presented in subsequent sections.

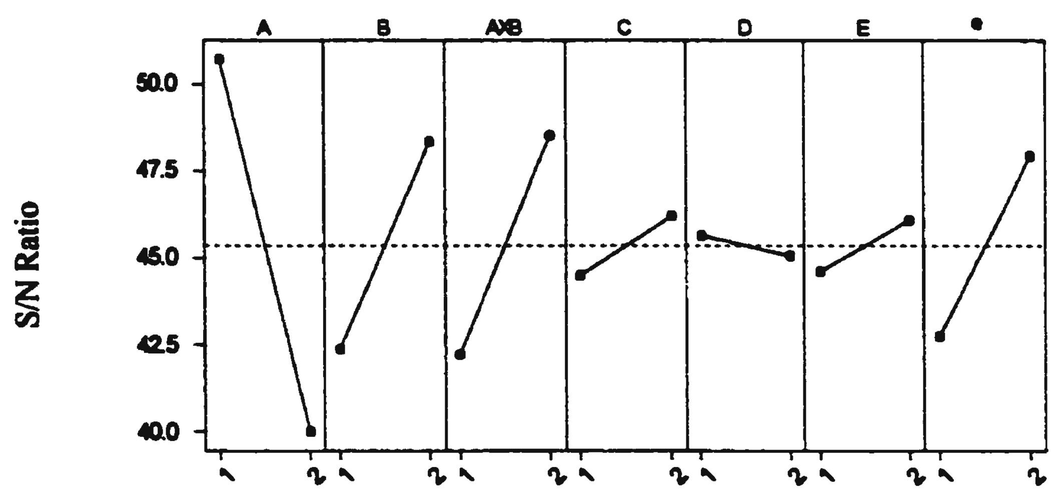
5.4.8.3 Part Temperature

Details of the average plots and ANOVA for part temperature are as follows:

5.4.8.3.1 Average Plots

The average plots for S/N ratios for all factors are shown in Fig. 5.5.

Factors



Factor levels

Average plots for S/N ratios of Temperature
Figure 5.5

S/N ratio average plots help identify the *control factors*, i.e., the factors which affect the variability of the response. Making average plots is fairly simple. For each control factor, the average of the S/N ratio values is calculated at each level. For example, for factor A, average S/N ratio at level 1 is:

$A_1 = (40.6982 + 48.4846 + 59.6349 + 54.0965) / 4 = 50.7296$

Similarly, average S/N ratio at level 2 is:

$A_2 = (40.8959 + 39.4404 + 36.8153 + 42.8145) / 4 = 39.9914$

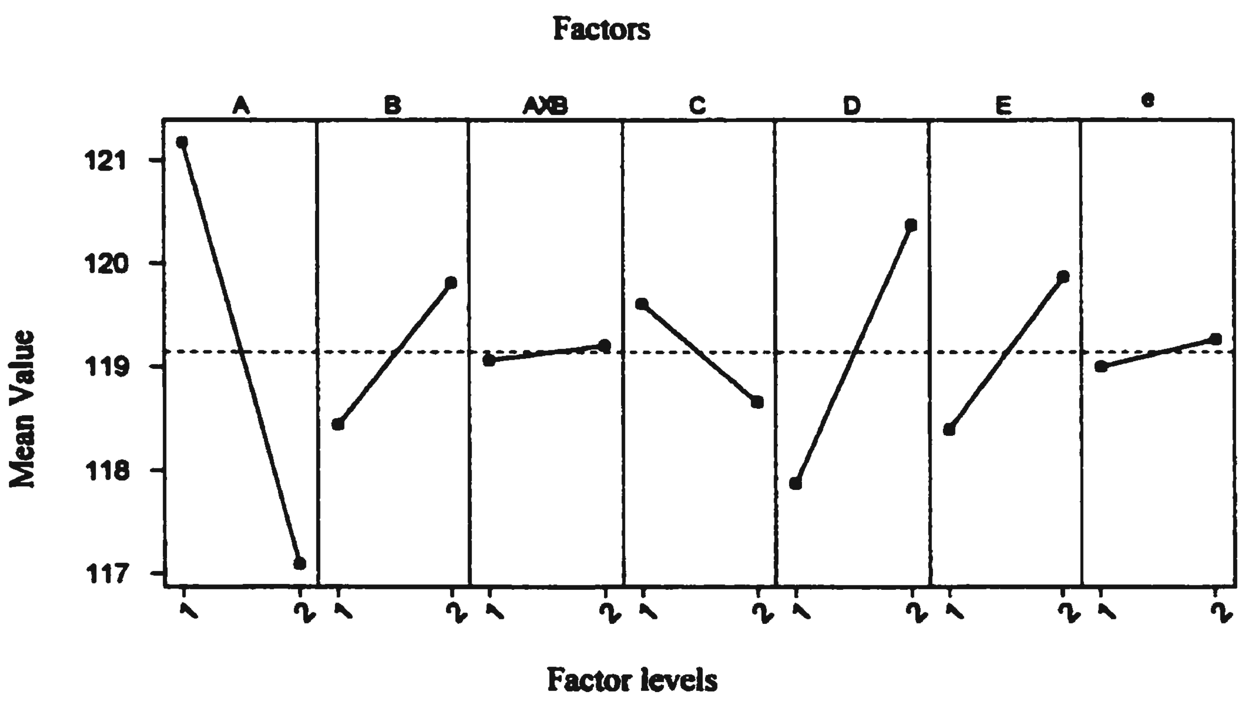
Both average values are plotted against their respective levels, and an average plot is obtained. Similarly, average plots can be obtained for other factors. The larger the difference in the average S/N ratios at the two levels, the larger is the factor effect on the response.

Interpretation of S/N plots

The graphs for S/N ratios reveal that factor A viz., heater speed is the most significant control factor as it has the largest effect on the response. The interaction AxB, between heater speed and heater temperature, has the second largest effect followed by heater temperature (B). The other factors C, D and E are not significant. Since the higher the value of the S/N ratio for a factor, the better it is, level 1 is the best choice for factor A, since it corresponds to the higher S/N ratio, while for both B and AxB, level 2 gives the higher S/N ratio.

From the average plots, we conclude that the optimum levels for the control factors are A_1, B_2 and $(AxB)_2$.

Average plots for the mean values are shown in Fig. 5.6. These plots were obtained for mean values using the same procedure as for the S/N ratios. Average plots for mean values help identify the *signal or adjustment factors*, i.e., the factors which have a



Average plots for Mean values of Temperature
Figure 5.6

significant effect on the mean. These factors help adjust the value of the mean response at the desired level.

Interpretation of mean value plots

The average mean plots show that factor A (heater speed) is the most significant adjustment factor followed by factor D (laser power), factor B (heater temperature) and E (crosshatch size). The rest of the factors are insignificant.

5.4.8.3.2 ANOVA for part temperature (S/N ratios)

The ANOVA table for S/N ratios of the part temperature is shown below.

Factor	Pool (Yes/No)	dof	Sum of squares (SS)	Mean square (MSE)	F-ratio (F)	SS'	Percent contribution (P)
A	No	1	230.5674	230.5674	14.26*	214.3974	48.16
B	No	1	71.0557	71.0557	4.39**	54.8875	12.30
AxB	No	1	79.7275	79.7275	4.93***	63.5575	14.24
C	Yes	1	5.7658	5.7658			
D	Yes	1	0.6316	0.6316			
E	Yes	1	4.3072	4.3072			
e		1	53.9890	53.9890			
Total		7	446.0469				100.00
e (pooled)	(64.6963)	(4)	64.6963	64.6963			25.39

*At least 95% confidence, ** At least 75% confidence, *** At least 90% confidence

ANOVA Table for Part temperature (S/N ratios)
Table 5.6

Explanation of the ANOVA table

ANOVA is a statistical tool which is used to identify the factors that have an effect on the variation of the response and to determine the relative effect of the different factors. Detailed treatment of ANOVA is given in references [34, 36, 46].

For the purpose of interpreting the ANOVA tables used in this study, a concise description of the salient features of ANOVA is given as follows.

ANOVA is all about determining whether certain factors have an effect (i.e., cause a change) in the magnitude of the response being investigated, and if yes, how strong is the factor effect. We will explain the ANOVA when the response is the S/N ratio.

The following steps are important in conducting the ANOVA:

- The first step is to determine the sum of squares. The following formula is used for computing the sum of squares (SS) for a particular factor, say, X.

  $$SS = \frac{(X_{1'} - X_{2'})^2}{N}$$

  where,

  $X_{1'}$ = sum of all S/N values at level 1 of factor X

  $X_{2'}$ = sum of all S/N values at level 2 of factor X

  N = the total number of S/N values in the experiment

For example, for factor A,

$$SS_A = \frac{(A_{1'} - A_{2'})^2}{N} = 230.5674$$

$A_{1'}$ = sum of all S/N values at level 1 of factor A

= 40.6982 + 48.4846 + 59.6349 + 54.0965 = 202.9142

$A_{2'}$ = sum of all S/N values at level 2 of factor A

= 40.8959 + 39.4404 + 36.8153 + 42.8145 = 159.9661

N = 8

Similarly, the SS can be calculated for the rest of the factors.

- Then the mean square (MS) or variance (V) for each factor/interaction and for the error (e) is calculated by dividing the SS of each factor/interaction and error by its respective degrees of freedom (ν). The formula is given as,

  $$MS = \frac{SS}{\nu}$$

- The mean square for error is called mean square error (MSE) or error variance. Error variance is a measure of variation due to all uncontrolled noise including measurement error.

- In the next step, *pooling* is carried out to pool the insignificant factor effects in order to get a better estimate of the error variance. As a rule of the thumb, either all the effects having sum of squares (SS) values smaller than the error sum of squares (SS_e)

are added to the SS_e, or all the factor effects having very low values of SS are added to the SS_e until the error *dof* is approximately equal to half of the total *dof* for the experiment. The *dof* for the pooled error is now the sum of the *dof* of the existing error and the *dof* of all of the pooled factors.

- The F ratio is then calculated. The F ratio measures the effect of each factor/interaction relative to the error. F ratio is the ratio of the mean sum of squares due to a main/interaction effect to the error mean square. A large value of F means that the effect of that factor is large as compared to the error variance. Also, the larger the value of F, the more important that factor is in influencing the process response. So, the values of F can be used to rank the order of importance of the factors. Statistically, the F ratio is compared with certain critical values of the F ratios provided in tables in order to determine the degree of confidence that a particular factor effect is indeed influential. For example, for factor A, after suitable comparison of the F ratio with the critical value from the F table, we can say with a 95% level confidence that factor A has a large effect on the response.

- The next step is determining the percent contribution. Percent contribution determines the percentage of contribution of each factor/interaction to the total variation observed in the experiment. Percent contribution indicates the relative power of a factor/interaction to reduce variation. If the factor/interaction levels were to be controlled precisely, then the total variation can be reduced by the amount indicated by the percent contribution.

Percent contribution is calculated as follows,

$$P = \frac{(SS') \times 100}{SS_T}$$

where,

$SS' = SS - MSE\ (\nu)$

SS = sum of squares for the factor

MSE = Mean square error or error variance

ν = degrees of freedom for the factor

SS_T = Total sum of squares = Sum of squares of all factors, interactions and error

The above explanation of ANOVA describes all of the steps required for interpreting the ANOVA table for the S/N ratio. Similarly, ANOVA can be performed and interpreted for the mean temperature.

From the ANOVA table for S/N ratio, it is obvious that heater speed (A) is the most significant control factor (with a percent contribution of 48.16% and F ratio of 14.26), followed by the interaction (AxB) and heater temperature (B) both of which have a moderate effect. The rest of the factors, viz., cutting speed (C), laser power (D) and crosshatch size (E) are insignificant and have been pooled into error. Thus, the control factors/interactions are A, B and AxB.

5.4.8.3.3 ANOVA for part temperature (mean value)

The ANOVA table for the mean value of the part temperature is shown below.

Factor	Pool (Yes/No)	dof	Sum of squares (SS)	Mean square (MS)	F-ratio (F)	SS'	Percent contribution (P)
A	No	1	30.65	30.65	45.75*	30.57	56.08
B	No	1	3.80	3.80	5.67**	3.72	5.85
AxB	Yes	1	0.04	0.04			
C	Yes	1	1.83	1.83		1.75	
D	No	1	12.56	12.56	18.75***	12.48	22.24
E	No	1	4.45	4.45	5.64****	4.37	7.07
e		1	0.13	0.13			8.76
Total		7	53.46				100.00
e (pooled)		(3)	(2.00)				

*At least 90% confidence, **At least 99% confidence, ***At least 97.5% confidence,

****At least 90% confidence

ANOVA Table for Part temperature (Mean)
Table 5.7

From the ANOVA table, it is obvious that heater speed (A) is the factor that has the most significant effect on the mean value of the part temperature. Factor A has a percent contribution of 56.08 % and F ratio of 30.57). The next significant factor is laser power

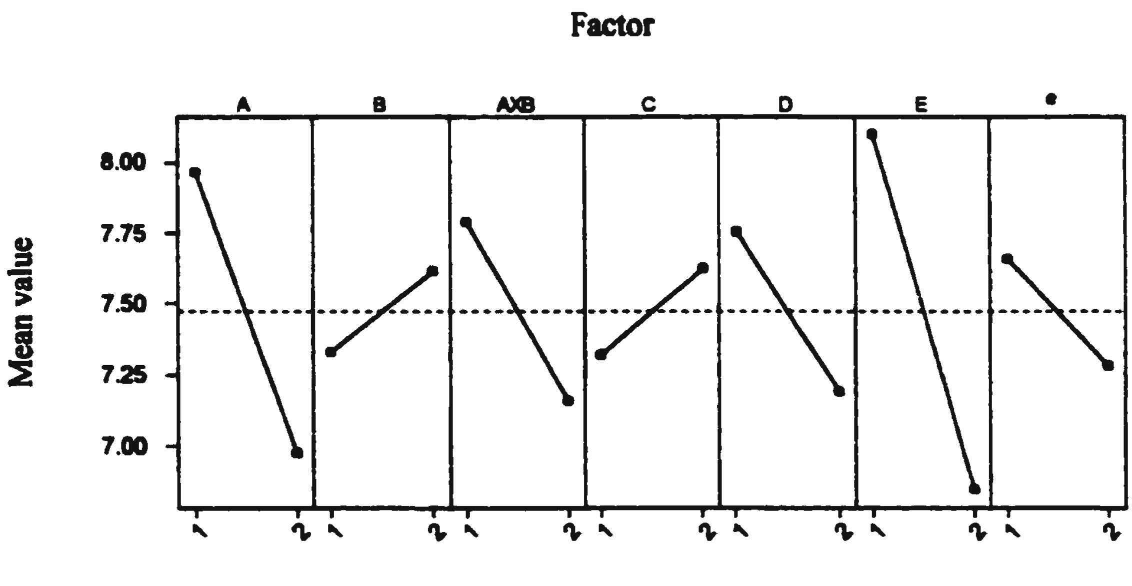
(D) with a percent contribution of 22.24%. crosshatch size (E) and heater temperature (B) have a mild effect. The rest of the factors, viz., cutting speed (C), laser power (D) and interaction AxB are insignificant and have been pooled into error. Thus the adjustment factors are A, D, E and B.

5.4.8.4 Part build-time

Details for the average plots and ANOVA for part build-time are as follows:

5.4.8.4.1 Average Plots

The average plots for mean values are shown in Figure 5.7.



Average plots for Mean values of Time
Figure 5.7

The average plots show that crosshatch size (E) is the factor that has the most significant effect on the mean value of the part build-time. Heater speed (A) has the next largest effect. Interaction AxB and laser power (D) have a moderate effect. The rest of the factors, viz., cutting speed (C) and heater temperature (B) have insignificant effects. Thus the adjustment factors based on the plots are E_2, A_2, $(AxB)_2$ and D_2.

5.4.8.4.2 ANOVA for Part build-time (Mean)

The ANOVA table for the mean value of the part build-time is shown below.

Factor	Pool	dof	Sum of squares (SS)	Mean square (MSE)	F-ratio (F)	SS'	Percent contribution (P)
A	No	1	1.965	1.965	9.27*	1.753	24.34
B	Yes	1	0.161	0.161			
AxB	No	1	0.803	0.803	3.79**	0.591	8.20
C	Yes	1	0.188	0.188			
D	No	1	0.641	0.641	3.02***	0.429	5.96
E	No	1	3.156	3.156	14.89****	2.944	40.88
e		1	0.287	0.287			
Total		7	7.201	7.201			100.00
e (pooled)		(3)	0.636	0.636			

*At least 90% confidence, **At least 75% confidence, ***At least 75% confidence,
****At least 90% confidence

ANOVA Table for Part build-time (Mean)
Table 5.8

The ANOVA table shows that crosshatch size (E) is the factor that has the most significant effect on the mean value of the part build-time. Factor E, has a percent contribution of 40.88 % and an F ratio of 14.89). The next significant factor is heater speed (A) with a percent contribution of 24.34%. Interaction AxB and laser power (D) have a small effect. The rest of the factors, viz., cutting speed (C) and heater temperature (B) are insignificant and thus have been pooled into error. Thus the adjustment factors are E, A, AxB and D.

5.4.9 Selection of optimum levels

The next step was to analyze the results of the data analysis and select the optimum combination of factors that would help achieve the objectives of the experiment.

Based upon the average plots and ANOVA table for S/N ratios for part temperature, the following optimum factor levels were chosen for reducing the process variability:
A_1, B_2, $(AxB)_2$. As discussed before, A_1 i.e., heater speed at level 1 has the most significant effect on the S/N ratio for part temperature followed by heater temperature at level 2 (B_2) and their interaction (AxB), also at level 2.

For mean response, Heater speed (A) was the most significant factor. But, it was also a control factor, as it had the largest effect on the S/N ratio. Therefore, heater speed was not chosen as an adjustment factor, since an adjustment factor is one which has a large effect on the mean but null or negligible effect on the S/N ratio. Laser power (D) had a significant effect on the mean but a negligible effect on the S/N ratio. Therefore Laser power was selected as an the adjustment factor. Since the maximum part temperature at level 1 of factor D was more than 120 F, level 2 was selected for D, as it would keep the maximum part temperature from rising above120 F. Since the rest of the factors viz., cutting speed (C) and crosshatch size (E) were not very significant, any of their levels could be chosen.

In the case of part build-time, since the focus was on reducing the time to the minimum possible and variability was not a concern, the average plots and the ANOVA for the mean were consulted. The information about factor levels derived for optimizing part temperature was considered while choosing the factor levels for part build-time, and finally the optimum levels for the whole process.

The most significant factor was the crosshatch size (E) and level 2 corresponded to the minimum possible value of build-time. Also, the crosshatch size was not significant as far as the part temperature was concerned. Therefore, there was no conflict in choosing level 2 for factor E. The next significant factor for the mean time was factor A i.e., Heater speed, with level 2 corresponding to lesser build-time. But, in case of heater speed, level 1 was significant as far as the part temperature was concerned. Since part temperature was the response of major concern for the experiment, it was decided to choose level 1 of the factor A for the whole process. (Also, the most significant factor for the build-time, crosshatch size (E) had already been chosen at level 1, the level most conducive to reducing build-time.) Next in the list was the interaction AxB, which was significant at level 2 for build-time and the choice coincided with that for the part temperature. Laser power (D) at level 2 had a small effect on build-time. But Laser power at level 1 was the crucial adjustment factor for part temperature. Thus, factor D was chosen at level 1 for the whole process. Factor C i.e., cutting speed was not significant for either response, therefore any level could be chosen for this factor. Level 2 was selected.

Thus, the final optimum settings derived for the LOM process are presented in the following table.

Factor	Level	Value
Heater speed	1	1.5 ips
Heater temperature	2	340° F
Cutting speed	2	18 ips
Laser power	1	12.5 W
Crosshatch size	2	1.00 inches

Optimum settings
Table 5.9

5.4.10 Confirmation Trials

In order to verify the derived optimum conditions, confirmation trials were conducted for the shoe, which was the test part for the study. Two trials were carried out. The observed values of the response variables are shown in Table 5.10 (p.175).

Part	Trial #	Max. in-process part temperature (°F)	Part build-time (Hrs.)
Shoe	1	119.93	7.09
	2	119.97	7.14

Confirmation trial results (Shoe)
Table 5.10

The two confirmation trials conducted to validate the derived optimum settings yielded reasonably good results for the test part; a maximum in-process part temperature of 119.93° F and 119.99° F and a build time of 7.09 hours and 7.14 hours for each trial respectively.

The above table shows that reasonably good results were obtained. The maximum in-process part temperature for both trials did not exceed 120° F and a build-time of around 7 hours was achieved.

To ascertain the amount of improvement that had been achieved in the response variables compared to the process settings previously used, comparative trials were carried out for the shoe using normal settings. The following results were obtained.

Part	Trial #	Max. in-process part temperature (°F)	Part build-time (Hrs.)
Shoe	1	121.98	8.56
	2	121.58	8.54

Comparative trial results (Shoe)
Table 5.11

Thus, a comparison of results obtained by optimum and normal process settings revealed that a definite improvement had been achieved for both the quality characteristics. This illustrated that Taguchi method was a potentially successful tool for LOM process optimization.

To further test whether the settings would work for similar parts, another test part, a concept model of a Television remote control (Fig. 5.8), was designed. (Part drawings showing basic dimensions are given in Appendix 4).

Television Remote control
Figure 5.8

The remote control was comparable to the shoe in terms of dimensions and complexity. Two trials were conducted in this case as well. The results obtained are shown in the following table.

Part	Trial #	Max. in-process part temperature (°F)	Part build-time (Hrs.)
Remote control	1	119.96° F	3.51
	2	119.94° F	3.56

Confirmation trial results (Remote control)
Table 5.12

The results were desirable. In this case also, comparative trials were carried out with the previously used process settings. The results are shown in Table 5.13.

Part	Trial #	Max. in-process part temperature (°F)	Part build-time (Hrs.)
Remote control	1	124.62	5.06
	2	124.83	5.09

Comparative trial results (Remote control)
Table 5.13

The comparison of results again demonstrated that TM had resulted in considerable improvement.

It was then decided to further extend the settings to parts with shapes and sizes entirely different from that of the shoe.

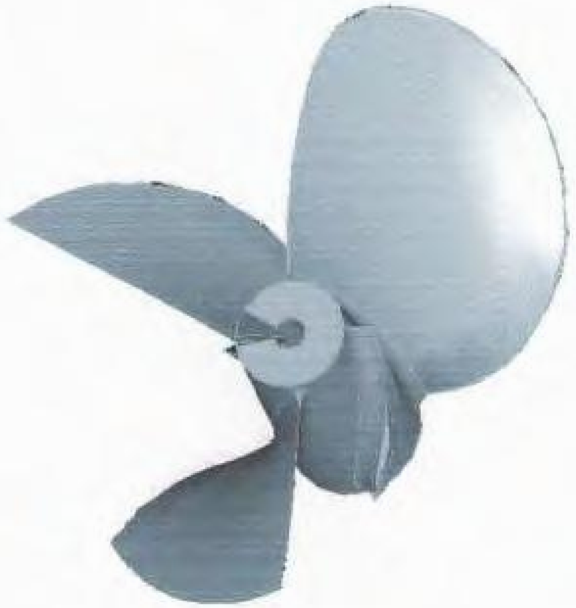
Three different parts, viz., models of a propeller (Fig. 5.9), jet (Fig.5.10) and a catamaran (Fig.5.11), were manufactured using the derived optimum settings. Part drawings are given in Appendix 4. The response results are displayed in the following table

Part	Max. in-process part temperature (°F)	Part build-time (Hrs.)
Propeller	119.79	8.31
Jet	119.80	6.44
Catamaran	119.81	7.50

Trial results (Propeller, Jet, Catamaran)
Table 5.14

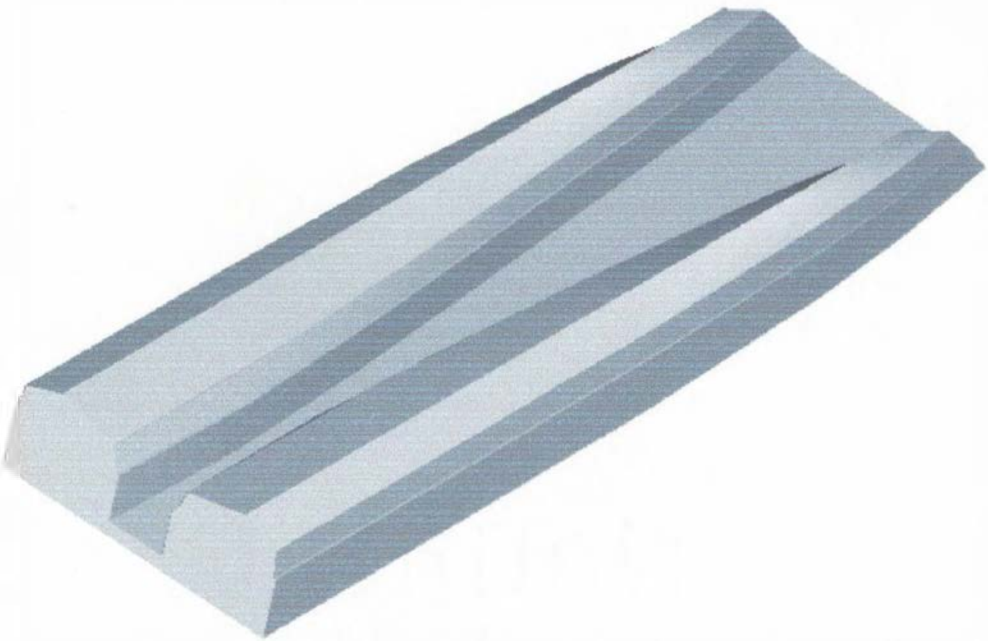
The above results show that the process settings produced reasonable results in terms of maximum in-process part temperature and part build-time even for parts that were considerably different in shape and size from the test part family.

Thus, the derived normal settings were recommended for LOM manufacturing using LPH 042 paper.



Propeller
Figure 5.9

Jet model
Figure 5.10



Catamaran
Figure 5.11

5.5 Conclusions and Suggestions for further research

The main objective of the study was to investigate the potential of Taguchi method as a RP process optimization tool. Laminated object manufacturing (LOM) was the RP process under consideration. The material used was LPH 042 paper. The LOM process was to be optimized such that the maximum in-process part temperature did not exceed 120° F and minimum part-build time was achieved. A screening experiment using L_8

Orthogonal array was conducted to identify the factors that were influential in affecting the maximum in-process part temperature and part build-time which were the quality characteristics to be optimzed. Heater speed, heater temperature, laser power and crosshatch size turned out to be the factors having the largest effect on the desired quality characteristics. After suitable analysis of results, optimum settings for the factors were determined. The confirmation trials conducted to validate the optimum settings yielded the desired results. The settings proved to be optimum for parts of the same family having size, geometry, and complexity comparable to the test part. These settings when extended to parts of different geometry and complexity again yielded good results. Thus, it was concluded that the derived settings could be used as standard optimum settings for the LOM process when LPH 042 paper is the building material.

In the above study, the parameters of the process were optimized in order to solve delamination problems and improve process time. However, Taguchi method studies can also be carried out to optimize quality characteristics like dimensions, strength, surface finish etc., for LOM prototypes. Generally, the requirement for these quality characteristics arises if the prototypes are being used for concept testing. For example, a prototype propeller being used for fluid flow tests would require precise profile, surface finish etc. Also, in this study, the LOM process was optimized for parts built with LPH 042 paper. The process can be similarly optimized for LPH 082 paper which has a thickness of 0.008", twice that of LPH 042 paper. The above mentioned possibilities can thus be considered for further exploring the potential of Taguchi method for LOM process optimization.

On the whole, the LOM process optimization case study, illustrated in this chapter, validates the potential of TM as front-end NPRP tool. Thus, while implementing NPD, TM can prove to be a highly effective tool with major impact on the front-end process stages, thus leading to high quality, low cost and accelerated products and processes.

Chapter 6

6. Overall Conclusions and Suggestions for Future work

This dissertation explored the concept of new product development in the manufacturing industry with an emphasis on the NPD process. In the context of the modern fast paced, quality conscious manufacturing environment, a NPD process model called the NPRP (new product realization process) model was devised for facilitating the efficient realization of high quality, low cost new products at an accelerated pace.

The five-phased model encompasses the various stages of NPD right from the idea generation stage to the post product-launch stage, and provides a systematic and holistic process for successful new product realization.

The focus of the NPRP model is on the process front-end wherein the maximum benefits in terms of achieving high quality, low cost and reduced development times can be attained. One of the tools for achieving these benefits is the Taguchi method. The NPRP model investigated the potential of applying Taguchi method as a front-end NPD tool by exploring its application in the concept design stage in the context of Rapid prototyping.

The type of RP process considered was laminated object manufacturing (LOM). TM was used for optimizing the LOM process. The material used was LPH 042 paper. The process was optimized in terms of obtaining a desired value for the maximum in-process part temperature in the range of 118 F-120 F (to improve part quality) and reducing the part build-time. A screening experiment was conducted using an L_8 orthogonal array. After conducting appropriate experimentation, the factors which had the largest effect on the quality characteristic were identified as heater temperature, laser power and crosshatch size. After analyzing the results, optimum settings for the factors were determined. These settings were validated through confirmation trials. The desired value of temperature was achieved and the build-time was reduced as well. The settings thus obtained proved to be optimum for parts belonging to the same family as the test part, based upon size, geometry and complexity. The settings when extended to parts of different geometry and complexity again yielded good results. This led to the conclusion that the derived optimum settings could be used as standard optimum settings for the LOM process using LPH042 paper. The experimentation was carried out at the Manufacturing Technology Center (MTC) which is a part of the Industrial Outreach group within the Faculty of Engineering and Applied Science at MUN.

The optimization of the LOM process establishes the validity of using Taguchi method as a quality-engineering tool for RP and hence as a front-end process tool for the NPRP model.

The study in this dissertation was concerned with optimizing the LOM process parameters in order to solve quality problems and improve process time. However other possibilities can be considered for future work in LOM process optimization. Taguchi method studies can be used for optimizing quality characteristics like dimensions, strength, surface finish etc., for LOM prototypes used in concept testing. Also the process can be optimized for the other LOM papers, like the LPH082 paper.

As far as the NPRP model is concerned, suggestions for future work include customizing the basic process infrastructure provided by the NPRP model to develop a working model for a NPD project in a real life industrial case study and eventually implementing and validating it.

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Appendix 1

Kotler's Model of the NPD Process

Stage 1 - Idea Generation

The new product development process begins with the search for ideas. New product ideas are obtained from several sources including customers, competitors, employees, distributors / agents, consultants, inventors and top management. Von Hipel (1978) has shown that the highest percentage of ideas for new industrial products originates with customers. Idea generation can also be carried out through structured creative techniques: really good ideas come out of inspiration, perspiration and techniques (Kotler, 1997). Sowery (1987) lists over 60 sources and techniques which can be used in the search for new products including specialized market research, ideas from company employees, ideas from the sales force, creativity-oriented techniques and competition-oriented techniques. Directors/top management define the product and market areas and determine the overall company objectives in terms of profit and ROI.

Stage 2 - Idea Screening

This stage involves screening the previously generated ideas to evaluate their potential success in the market place and includes examining their compatibility with the company resources as well as production costs. Thorough screening should sift out those ideas which are likely to fail at a subsequent stage, because the further a product is developed then the greater the cost to the company. There are a number of idea rating devices available to aid this phase of the development process.

Stage 3 - Concept Testing

Concept development and testing should be applied to any product, service or idea: an electric car, a new machine tool or a new service. Too often, top management thinks that the generation of an idea is the end of the process and that all that remains is to produce and sell the physical product. Levitt (1981) observed that ' everybody sells intangibles in the market place no matter what is produced in the factory: consumers buy concepts not ideas'. New products can encounter many ideas in the market place which could have been avoided if time had been devoted to effective concept development and testing.

Stage 4 - Marketing Strategy Development

When the first three stages have been successfully completed, the next stage involves developing a strategic plan for introducing the product into the market. This marketing strategy consists of three areas which generally need refining as the process progresses. First, the size, structure and behaviour of the target market, the planned product positioning, sales, market share and profit goals sought in the first few years. Secondly, the planned price, distribution strategy and the marketing budget for the first year. Thirdly, the long-term sales and profit objectives and marketing mix strategy over time.

Stage 5 - Business Analysis

This stage is designed to assess the business attractiveness by the preparation of sales, cost and profit projections to ascertain whether they meet the company's objectives. If the analysis is positive, then the concept can be moved to the next phase. However, the business analysis should be constantly monitored and refined as new information is obtained. Typical tools used in this phase include sensitivity analysis and / or risk analysis.

Stage 6 - Product Development

It is at this stage that a large increase in investment is required because the concept must be developed into a physical product. The essential elements of successfully developing a physical product as described by Coxhead and Davis (1992) are to ensure that it embodies the prime benefits described in the product-concept statement, that it performs as required, and that the production costs do not exceed the manufacturing budget.

Stage 7 - Market Testing

At this stage of the process, the product is placed in ' an authentic consumer setting' to test the reaction of customers and distributors and to accurately assess the marketing potential. This stage of the process takes on differing degrees of importance depending upon circumstances such as: the nature of competition, industrial or consumer markets, new or modified products. Industrial goods should be designed in co-operation with one or more of customers because it partially negates the need for extensive market testing. However, Kotler still recommends a ' product-use testing' process in which customers advise on the performance of the new product. Caution should be exercised at this stage because market testing can telegraph a company's intentions to the competitors, who may produce copies or reduce the price of competing products.

Stage 8 - Commercialization

This stage may result in the highest cost to the organization particularly if it is a product which requires new manufacturing facilities. Also, Kotler estimates that marketing costs can represent 57% of the sales during the first year. Key decisions at this stage include: when (timing of launch), where (national or regional launch), whom (targeting and positioning decisions) and how (introductory marketing strategy). There are high attrition rates in the NPD process, and many products are not developed because companies do not possess the necessary skills, knowledge or technologies to bring them to fruition. Therefore, it is vital that companies measure the various stages of development against their own strengths and weaknesses. Kotler's model provides key *decision gates* at which time decisions are made to: Go, Kill, Hold or Recycle.

Appendix 2

Glossary

Analysis of variance (ANOVA): This is a statistical procedure that uses mean sum of squares calculated from response data obtained in a statistically designed experiment to separate and then compare variability attributable to different factors influencing the response data.

Benchmarking: Benchmarking is a systematic method by which organizations measure their performance against that of the best-in-class organizations, determine how the best in class achieve those performance levels and use the information to meet or surpass the best performers.

Beta Testing: This consists of releasing the product after in-house testing to a select group of clients who use the product and supply useful feedback which can be incorporated in further improvement of the product before its market launch. E.g. beta testing is very popular among firms involved in developing new software programs. Beta testers agree to try out the programs, and return feedback to the developers who use the information to further enhance the programs.

Bill of Materials (BOM): This is a complete listing of all the components/subassemblies/raw materials and their individual quantities required for manufacturing a product

CAD Systems: These are computer aided 'drafting boards' that allow a user to define a new product by a).creating images and b).assigning geometric mass, kinematics, material and other properties to the product. The trend is towards CAD systems that create an electronic model of the product, including design intent.

Champion: A project champion is a person who takes responsibility to guide the project and see it through successfully despite all odds. He is usually a senior management personnel with considerable authority.

Co-located teams: In co-located teams, the members are located in one office or building in order to facilitate easy access, flow of information and hence better team work.

Concept tests: These study customer reactions to the proposed new product in concept form. The concept prototypes are often product models, visual sketches or computer-simulated models (depending upon the individual situations). Evaluation of product concepts is done prior to the commitment of major financial resources to either product development or business case analysis in order to establish confidence in the product idea and gauge customer reactions.

Concurrent Engineering: This is an approach to new product development where the product and all the associated processes, such as manufacturing, distribution and service are developed in parallel.

Customer site visits: This involves visiting customer sites in pre-product development stages (such as concept development) in order to acquire an in-depth perspective of customer requirements.

Degrees of freedom (dof): The number of independent parameters associated with an entity like a matrix experiment, or a factor is called its degrees of freedom.

Design for Assembly: Its goal is to make the product easier to assemble, thereby reducing cycle-time and waste during production.

Design for Manufacture: Its goal is to maximize ease of manufacture by simplifying design through part-count reduction, developing modular designs, minimizing part variation, designing a part to be multi-functional parts.

Failure mode effects analysis: This is a simple technique which identifies the potential problem areas of a product and initiates early corrective action to reduce their impact.

Focus groups: These are in-depth qualitative discussion-oriented interviews with a small number of carefully selected customers. Marketing firms use focus groups to determine how customers respond to new products.

Heavyweight Manager: A heavyweight manager controls all the project related issues and has full authority over the project team.

Matrix organization: This is a structure in which individuals, groups and managers continue to work within their specialist function departments but are assigned to work full-time or part-time under the direction of a project manger who is not their line manager. Such assignees are responsible to the project manger for their project work and to other functional mangers for activities that are not related to the project. Depending upon the level of authority of the functional/project managers, matrix organizations are classified as weak matrix, balanced matrix and strong matrix.

Normal Distribution: This is the probability distribution characterized by a smooth, bell shaped curve. The distribution is uniquely determined by its mean and variance.

Orthogonal Array: This is an array (matrix) of numbers whose columns are pairwise orthogonal. In every pair of columns all ordered pairs of numbers occur an equal number of times.

Performance Simulation: This involves the use of computer-based techniques in a wide range of applications such as simulating product -performance, processes, discrete events etc.

Pilot lot production: These are products made prior to the commencement of regular production, using regular production tools, processes, equipment, environment and cycle time in order to validate the established manufacturing systems and product technology.

Process owner: This is a person who is responsible for establishing and maintaining the new product development process in an organization.

Project scheduling techniques: These use of manual and computer based tools to plan and develop the time frame of a project, including tasks to be completed, resources required, checkpoints for accessing progress and major milestones. Project networking techniques such as CPM (critical path method), PERT (project evaluation review technique); and Gantt charts (bar charts) are the popularly used tools for project planning and scheduling.

Rapid Prototyping: These are systems that can create a physical prototype directly from a CAD representation.

Statistical Process Control (SPC): These are statistical techniques used to monitor, control and improve process performance over time by studying process variation and its source.

Taguchi Method: This is a quality tool for realizing high-quality/low-cost products with the help of statistical design techinques.

Team-building drill: These train personnel to give them the ability to work with diverse, multi-disciplinary team members in order to successfully accomplish a goal or objective.

Test Marketing: This is the marketing technique where a new product is introduced and advertised in selected markets prior to large-scale product launch. Test marketing is done to gauge consumer-reaction to the new product, estimate potential sales, potential market share and the effect on existing product mix.

Value Engineering: This a systematic approach to evaluating design alternatives that seeks to eliminate unnecessary features and functions and to achieve required functions at the lowest possible cost while optimizing manufacturability, quality and delivery.

Virtual Design: This involves the use of virtual reality technology to facilitate the design and development of products. Simulating product use prior to development helps to communicate the product concept to non-technical and technical audiences alike.

Voice of the Customer: This tries to identify customer requirements, needs and expectations of the product which are researched through customer-surveys, interviews, etc.

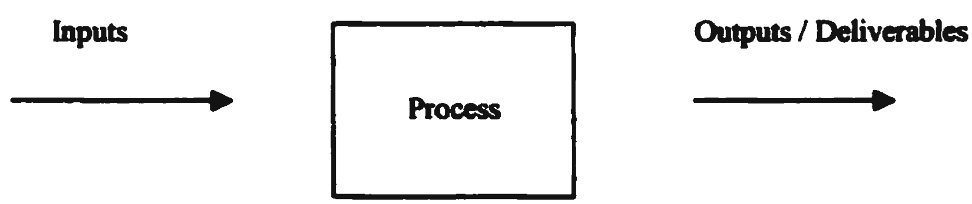
Quality Function Deployment (QFD): This is a detailed planning technique aimed at translating the 'voice of the customer' into company specifications at each major stage of the product introduction process.

Appendix 3

Input/Output diagrams

I/O diagrams are process-representation tools which help illustrate the objective of each phase, the desired outputs/deliverables and the inputs required to obtain the desired outputs.

The simple concept of I/O diagrams for process representation can be depicted as follows:

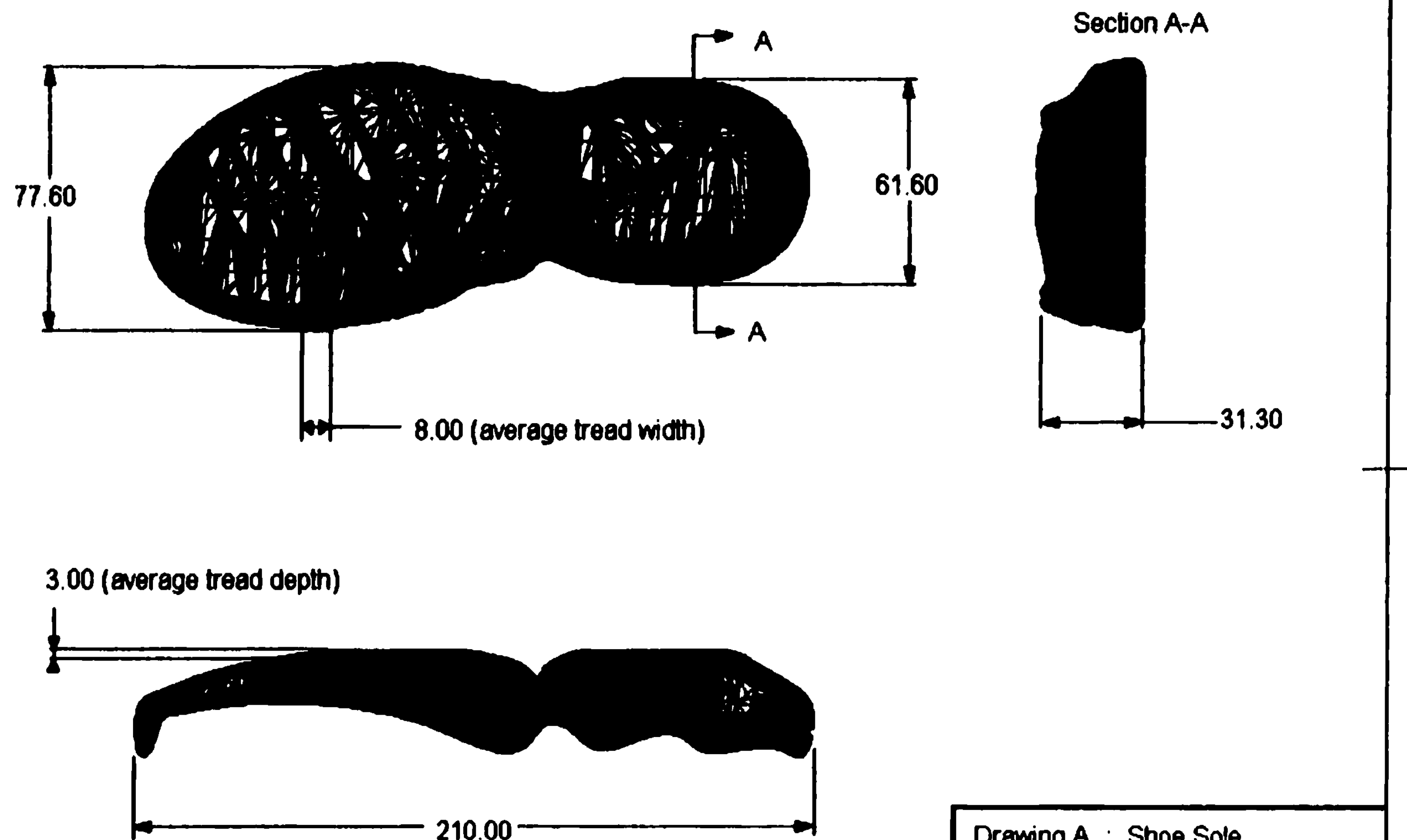


Steps:

- Define the process
- Specify necessary inputs
- Specify required outputs

Appendix 4

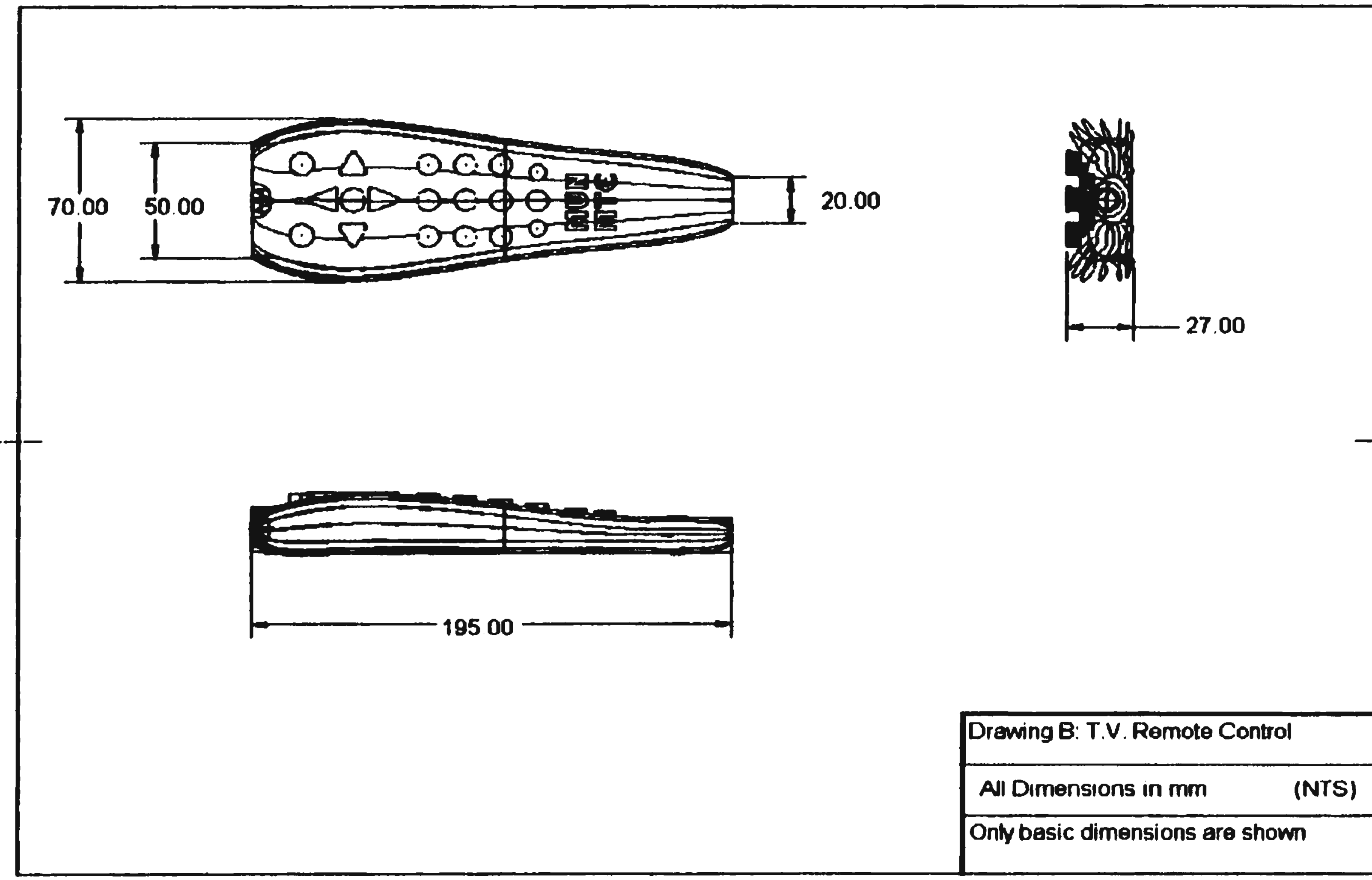
Part Drawings

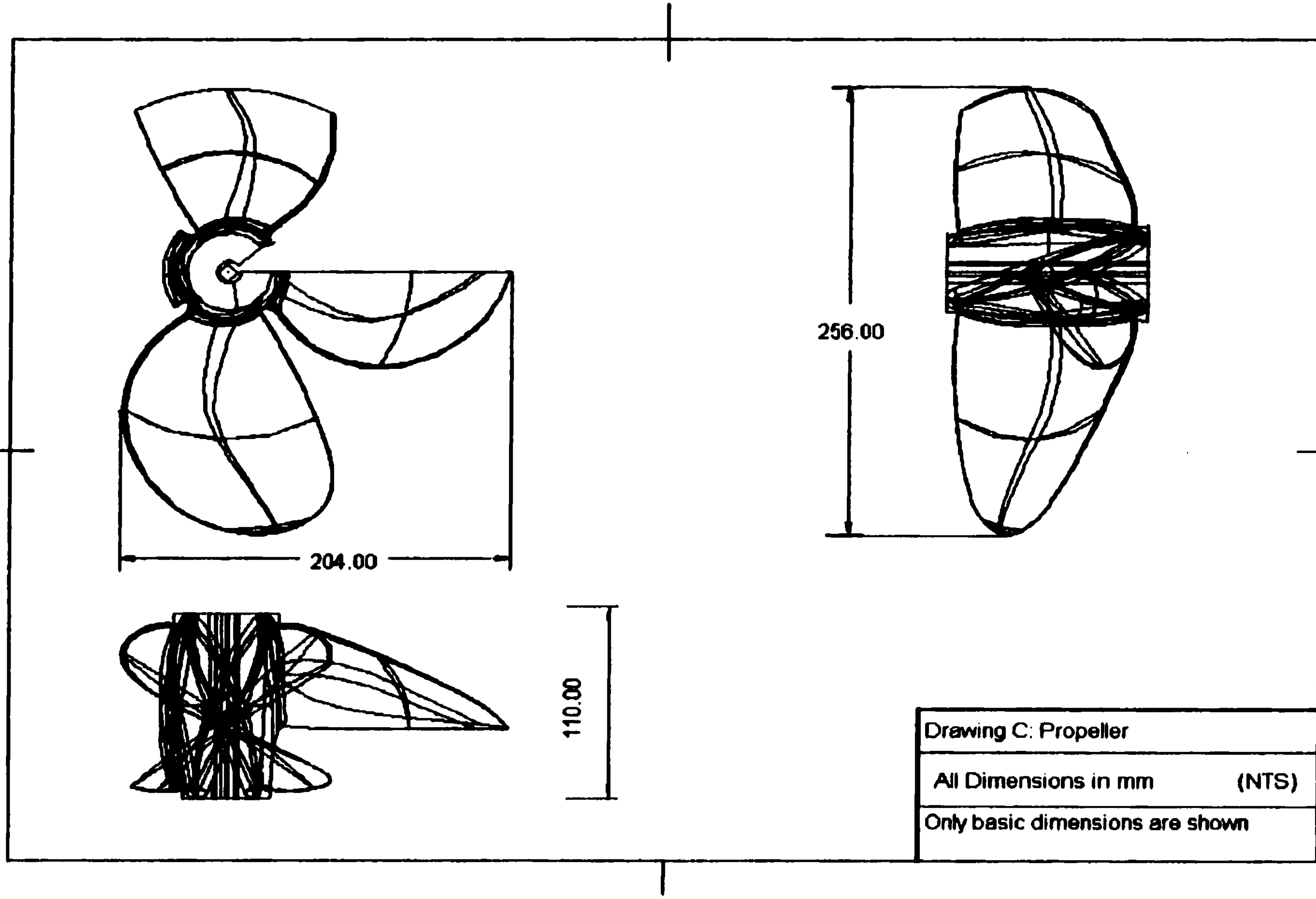


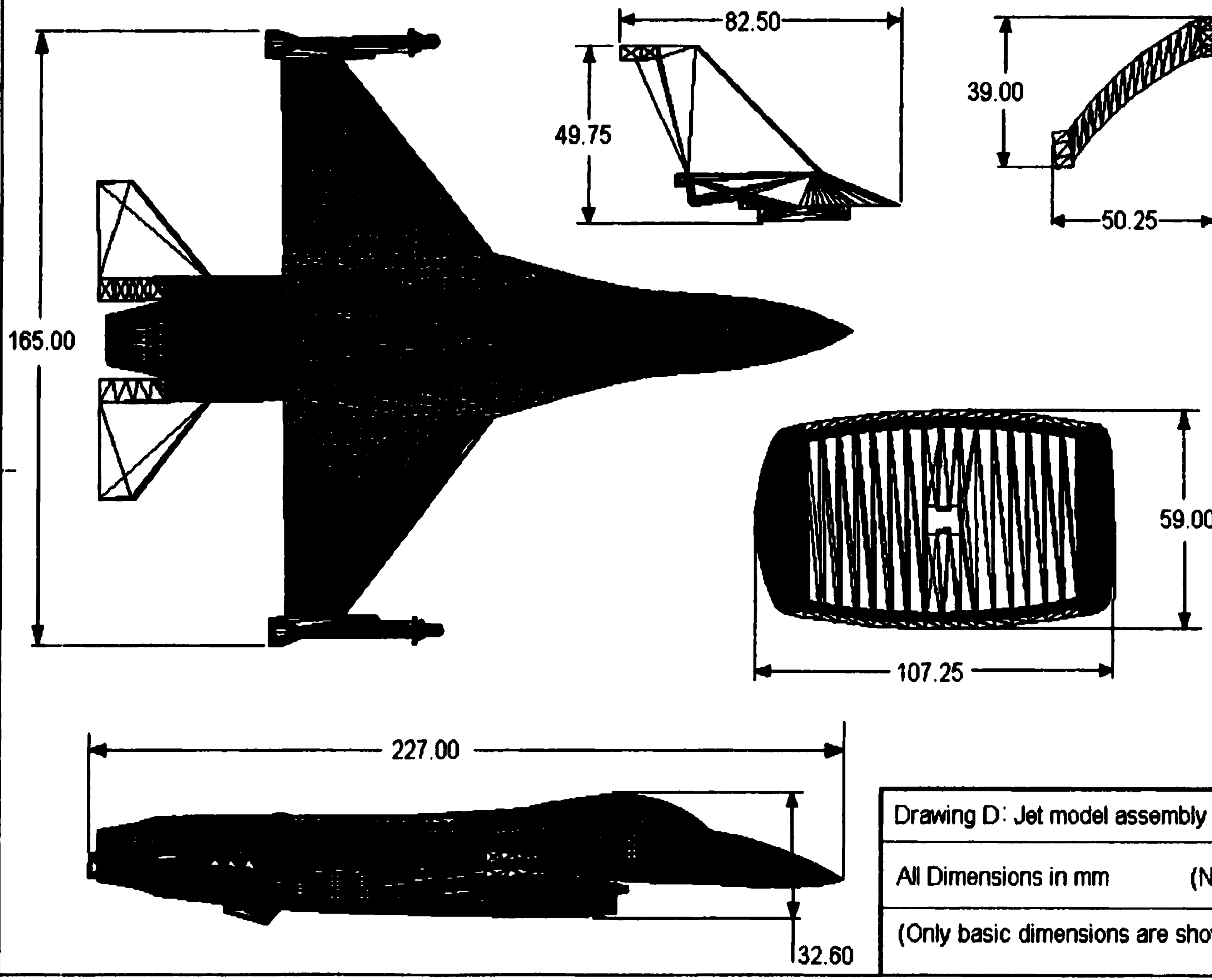
Drawing A : Shoe Sole

All Dimensions in mm (NTS)

Only basic dimensions are shown


70.00
50.00
20.00
27.00
195.00
Drawing B: T.V. Remote Control
All Dimensions in mm (NTS)
Only basic dimensions are shown

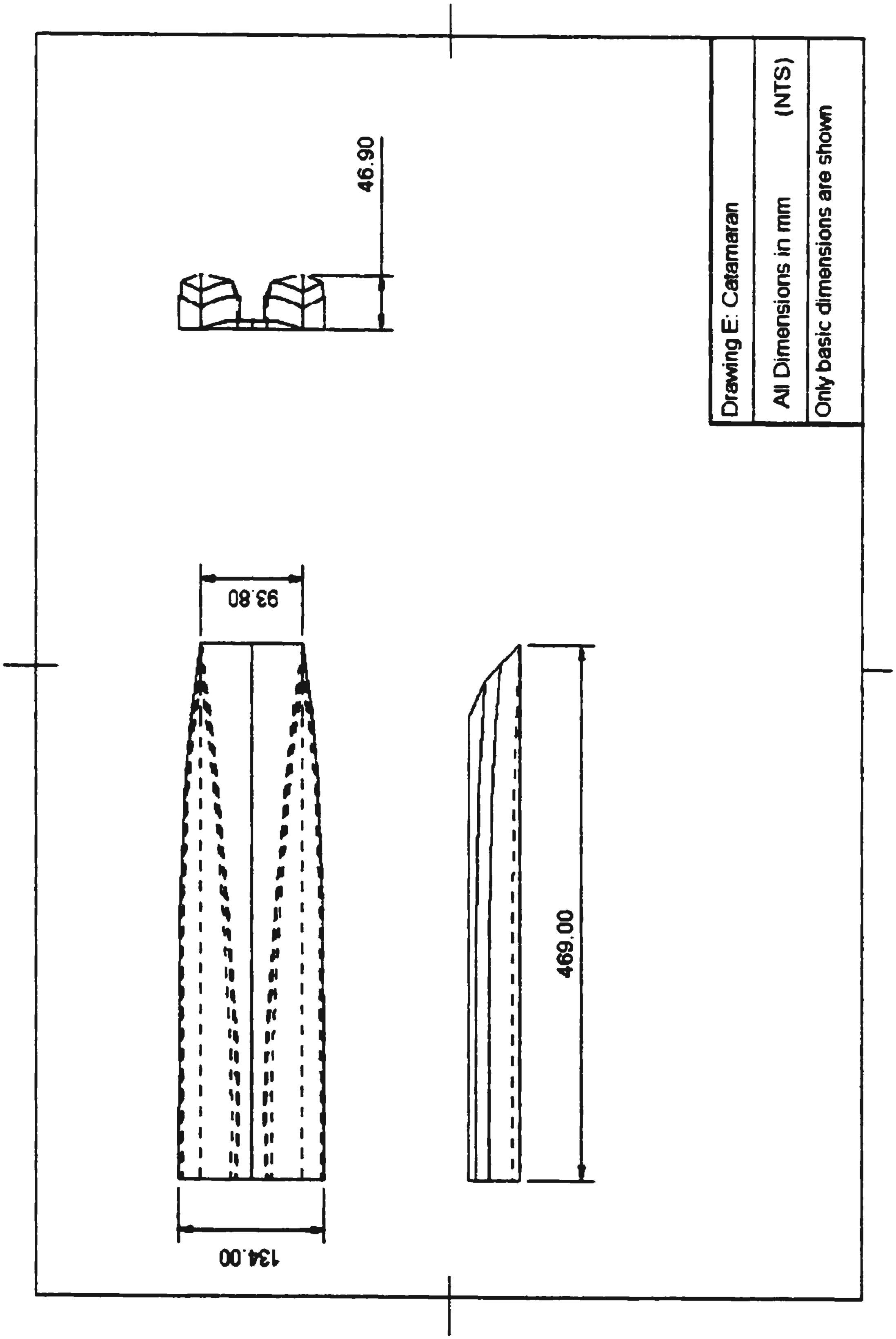

204.00
110.00
256.00
Drawing C: Propeller
All Dimensions in mm (NTS)
Only basic dimensions are shown



Drawing D: Jet model assembly

All Dimensions in mm (NTS)

(Only basic dimensions are shown)


Drawing E: Catamaran
All Dimensions in mm (NTS)
Only basic dimensions are shown
46.90
93.80
134.00
469.00