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Rapid Prototyping Technology Adoption Framework Development: Operationalization and Roadmap Generation for SMEs

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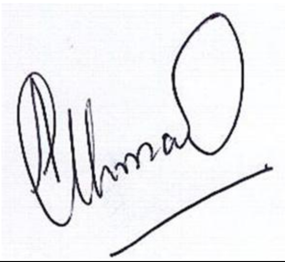
Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.



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Date: **10-02-2014**

Abstract

Recent uncertainty in world economies has changed the dynamics of the markets. The unprecedented increase in product flexibility requirements, short product life cycles, reductions in time to market and higher levels of product customisation are several attributes of the current and future scenarios. These global changes are affecting the way an organization operates and therefore have a significant impact on the manufacturing processes and the technology they use. The changing global picture has a profound impact on Small and Medium Enterprises (SMEs) but due to the limited human and technological competencies these organizations are unable to address the challenges of faster product introduction with high customer input and are therefore struggling to stay and remain in markets.

Rapid prototyping technologies (RPT) have tremendous potential to address these challenges, but despite its vast payback a significant proportion of SMEs are still not in use of this technology. The low adoption issue is quite complex and has multiple reasons including incomplete and inaccurate understanding of the environment in which it operates and inadequate assessment of internal business operations. These issues make selection of the right technology that meets their financial and technical goals more and more difficult. Evaluation of both external and internal environment and linking them with an emerging technology like RPT is a daunting task considering the SME's level of expertise. This generates a need for a simplified but practical and integrated approach for an expedient adoption of the RP technology

Development of an extensive and practical roadmap for an effective adoption of RP technology is the basis of this research, which intends to provide a detailed practical guide from strategic through to the operational level. This has been achieved through the development of frameworks, a Decision Support System for process selection, identification of the drivers of external and internal environment, market and competitor analysis. The analysis has been performed by employing the techniques like Analytical Hierarchy Process (AHP), value chain micro analysis of product development cycle and important performance (IP) Analysis.

The research has been conducted in two stages. The first stage involves the development and validation of a RP technology adoption framework, whereas the second stage focuses on the implementation of the developed framework in an industrial environment through action research. Two case studies were conducted; one in a developed and the other in a developing country to demonstrate the effectiveness of the proposed research in dynamic environments. The practical work provided an implementation mechanism for RP adoption through establishment of a technology link with the strategy in a real environment.

The result of the competitor analysis showed a clear gap between the current and desired position of the company to stay competitive. Application of Strategic Technology Adoption Framework (STAF) set the direction for technology requirements as a mismatch was found between current technology and what the market demands. Expert system for technology selection guided the companies towards the suitable RP equipment. Micro value chain analysis quantified the impact of RP on complete lifecycle of the product. These empirical findings provide evidence that RP technology have a great link with improving the desired competitive position of the company.

The research adds value to the previous knowledge in the area of technology road mapping (TRM) and technology selection by providing a robust and practical approach. This could have significant impact on the SMEs to expand their role in the global value chain by adopting the RP technology.

Publications

1. Ahmad A, Hasan M, Erik J (2008), 'Time Compression Technology: Why limited uptake in SME's. *2nd International Conference on Additive Technologies*. Ptuj Slovenia.

2. Ahmad A, Hasan M, Erik J (2009), 'A Strategic Framework & Key Drivers for RP Adoption. *The 33rd Rapid Prototyping Symposium 22-23 June.* Tokyo. Japan.

3. Ahmad A, Mazhar MI, Erik J (2009), 'Strengthening SMEs through Rapid Prototyping to meet future challenges Why & How? *14th Cambridge International Manufacturing Symposium* 24-25 Sep. Cambridge UK.

4. Ahmad A, Mazhar MI, Howard IM (2011), 'A systems approach for the effective adoption of rapid prototyping for SME's *2nd International Conference on Industrial Engineering & Operations Management* 22-24 Jan Kualalumpur, Malaysia.

5. Ahmad A, Mazhar MI, Howard IM (2012), 'A framework for the adoption of Rapid Prototyping for SME's: From Strategic to Operational *International Journal of Industrial Engineering: Theory Applications and Practice,* Vol.19 Issue 3, pp. 161-170.

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Contents

List of Tables

List of Figures

List of Abbreviations

TRM	Technology Roadmapping
SMEs	Small and Medium Enterprises
RP	Rapid Prototyping
AHP	Analytic Hierarchy Process
OECD	Organisation for Economic Cooperation and Development
EU	European Union
EEA	European Economic Area
ASTM	American Society for Testing and Materials
AM	Additive Manufacturing
RM	Rapid Manufacturing
IGES	Initial Graphics Exchange Standard
STL	Stereolithography
CAD	Computer Aided Design
3D	Three Dimensional
LOM	Laminated Object Manufacturing
SLS	Selective Laser Sintering
FDM	Fused Deposition Modelling
CNC	Computer Numerical Control
ETA	Effective Technology Adoption
AMTs	Advance Manufacturing Technologies
MNCs	Multinational Corporations
AR	Action Research
POM	Production and Operations Management
VSA	Value Stream Analysis
STAF	Strategic Technology Adoption Framework
MCDM	Multiple Criteria Decision Making
KSC	Kennedy Space Centre
NASA	National Aeronautics and Space Administration
DSS	Decision Support System
GVC	Global Value Chains

1

INTRODUCTION

Manufacturing plays a pivotal role in the economy of a country, whereas the industrial development is a strong indicator of a resilient economy. Manufacturing not only provides a key input to the other segments ranging from agriculture to defence but also creates jobs resulting in a prosperous society. SME contribute significantly to the national economy and in fact constitute a larger proportion of the countries manufacturing sector. These small and medium companies are a significant source of input to large companies, and at the same time they fulfil the vast requirements of domestic customers and markets.

*The global economic crisis supplemented by the high cost of energy has posed considerable threats to the companies especially on to SMEs. The environment in which these organizations are operating demand customized, low volume products at reasonable quality and price, so the quick response and flexibility have become indispensable determinants of success in global markets. Manufacturing companies in both developing and developed countries are affected by this changing mechanism of increased competition and new market dynamics. The current global financial

* Taken from Author's Paper (Ahmad et al., 2009)

crisis has created a new set of challenges with added pressure on local firms to compete in the markets.

A recent trend is globalisation which according to Dicken (1998) is “not only the geographical extension of economic activity across national boundaries but more importantly is the functional integration of such international dispersed activities”. In the process of globalisation companies devolve their operations in different parts of the world which constitute Global Value Chains (GVC). Two important features of GVC are production globalisation, which demands growth in industrial capabilities in developing countries and vertical disintegration of multinational corporations, which redefine their core competencies (Gereffi et al., 2005).

GVC covers a complete list of activities ranging from conception – production – final delivery to the customers and these activities are performed by firms located in different geographical locations of the world (UNCTAD, 2006). The organization of Economic Corporation & Development (OECD) which consists largely of developed nations also highlighted the issues faced by SMEs and their role in GVC. The challenges include (OECD, 2008)

i) “Awareness and understanding of the value chain dynamics and competitiveness.
ii) Inability to upgrade.
iii) Protect in house technology.
iv) To innovate.
v) Strict quality compliance”.

Global value chains pose a great threat and opportunities to the SMEs at the same time depending on their ability to respond to the GVC challenges and have certain common threads of issues and challenges in both developing and developed nations. The role of SMEs in developing countries has changed where they have become important partners of multinational companies as shown in Figure 1.1.

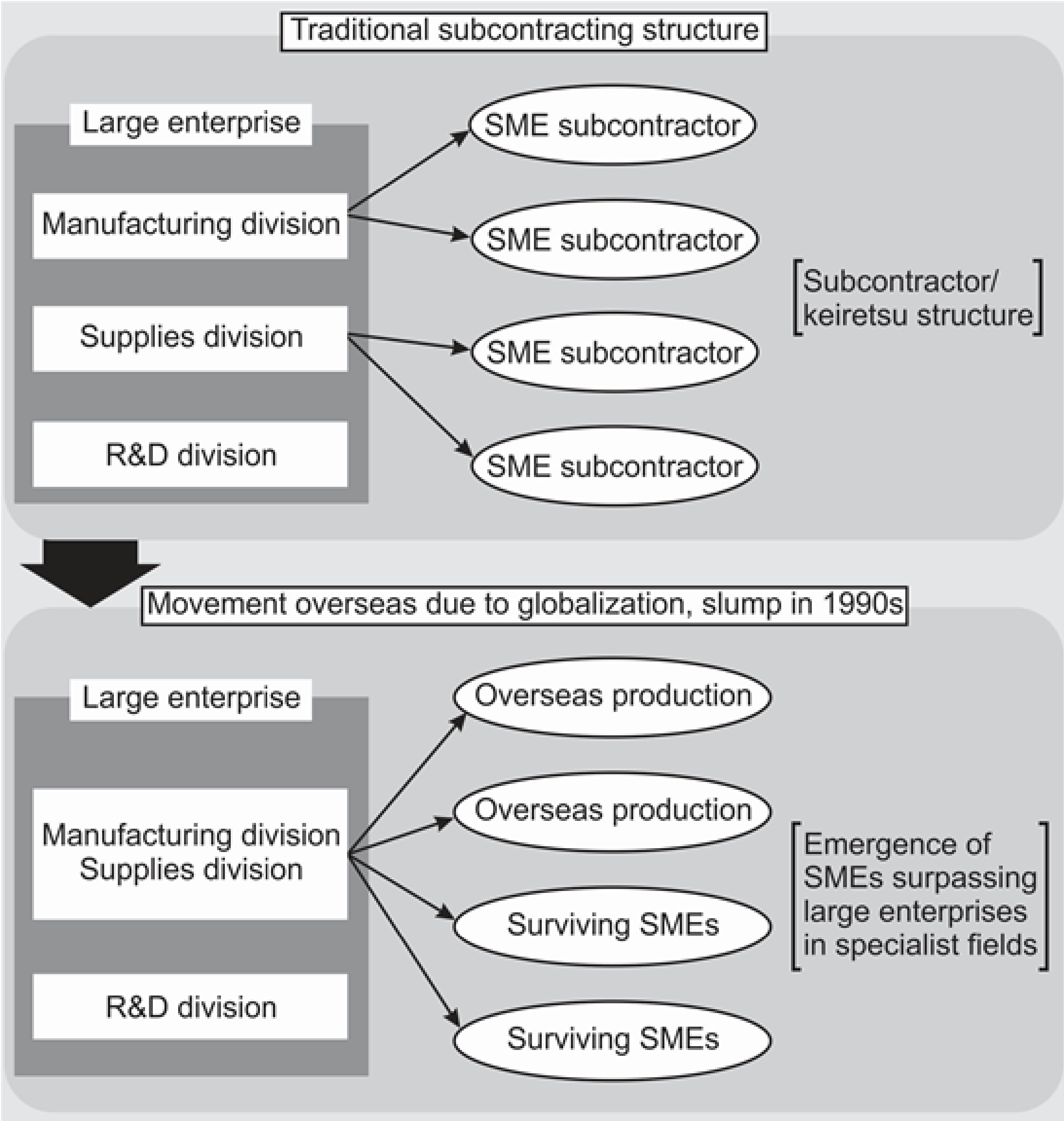


Figure 1.1: Changing Role of SMEs (JSBRI, 2005)

With the increased complexity of the products, the product life cycles and time to market are shortening. To ensure long term success, the manufacturers are required to concentrate on both markets and technology (IEA, 2009). In this rapidly changing scenario, the capacity building of SMEs can play a vital role particularly during the product development cycle, as the process can be regarded as a gateway to the international markets. However, in the case of SMEs it is ending with long lead time, high cost and poor quality where the production of complex products is almost impossible in a large number of companies. The reliance on old technology, inherent management issues of SMEs and unavailability of practical solutions specific to such companies are a few factors which are holding them to their current limited markets. Future changing scenarios where more production is required from them by large enterprises demands the awareness and adoption of latest technology and processes. This is one way which can ensure their effective role in GVC. The next section describes how RP can assist SMEs to tackle the global challenges.

1.1 Rapid Prototyping Technology & SMEs

Rapid Prototyping is additive manufacturing, which builds a part layer by layer. The inherent capability of this technology has made it an ideal candidate for producing parts of any complexity and through a range of applications like functional testing, form fit analysis or even the parts produced can be used as end product based on the material and equipment used. These advantages have great impact on the design-manufacturing cycle with a significant impact on lead time and the cost of the product which leads towards the increased capacity of the company. The rapid and unpredictable change in business environment has increased the risks for business operations and this technology must be addressed within the context of market turbulence (Kidd, 1997). With increasing importance of globalisation, the companies have realized an increased pressure on every sector of manufacturing, where the revolution of RP technologies have enabled companies to create the design in much shorter time to ease that pressure (Onuh & Hon, 2001).

From large multinationals to small companies the benefits of RP are striking and the companies which are using the technology are reporting significant reduction in the design-prototyping cycle, leading towards improved product quality (Wohlers, 1995)

Despite the ability of RP technology to address the challenges of SMEs like limited design and manufacturing, still only a small proportion of industry uses of this technology and this is predominantly true for SMEs.

“The general consensus is that less than 20% of the design and product development community use rapid prototyping. In the manufacturing engineering discipline the level of use is far less”(Grimm, 2004).

Reliance on traditional procedures, lack of understanding about the changing market requirements, linking technology with the market demands, selection of the right technology and its impact on business are some of the factors which can be blamed for low adoption of technology in SMEs. Practical adoption solutions which can guide adoption from strategic to operational level are hard to find resulting in the status quo being maintained by this critical sector, which is still not in use of this revolutionary technology.

1.2 RP Adoption through Technology Roadmapping

Technology Roadmaps (TRM) are an extraordinary tool to assist companies to predict the future requirements and also to help them to synchronize the business with changing demands. According to Phaal et al. (2004),

"Technology roadmapping is a flexible technique that is widely used within industry to support strategic and long-range planning. The approach provides a structured (and often graphical) means for exploring and communicating the relationships between evolving and developing markets, products and technologies over time. It is proposed that the roadmapping technique can help companies survive in turbulent environments."

Technology roadmaps need an astute understanding of markets and applications in order to define the products which leads towards the technological requirements (Groenveld, 2007). Albright and Kappel (2003) contend that market, product, technology and action plan must be considered to constitute a roadmap, which should be supplemented with other roadmaps like product development, technology and action plans. Holmes et al. (2004) argued the general belief regarding the technology roadmapping that they are for bigger companies only, but small companies are in equal need of such roadmaps, which link technology with business. This is going to be increasingly significant as smaller companies move up the value chain.

1.3 Aim of the Research

The aim of the research is to assist manufacturing companies with a specific focus on SMEs, through the development of a viable RP adoption roadmap equipped with frameworks, Decision Support Systems and practical tools to facilitate the adoption process from strategic to operational levels. The research also aims to quantify the impact on product development cycle to accelerate the RP technology adoption.

1.4 Research Objectives

The proposed research is aimed at helping the manufacturing companies, especially SMEs, by providing a technology selection and adoption framework. The study would specifically address the problems and difficulties associated with the selection and operationalisation of the rapid prototyping technology (RPT). The objectives would be:

i) Developing a comprehensive adoption framework in the form of interlinked processes.
ii) Identifying and developing strategic, tactical and operational decision factors, their corresponding attributes & indicators along with technology drivers.
iii) Demonstrating the strategy-technology link in the technology adoption process.
iv) Developing a computer based decision support system to facilitate the decision makers in the right process selection based on the requirements of their company.
v) Quantifying the impact of the rapid prototyping technology on the product life cycle, particularly on the product development cycle.
vi) To demonstrate the pitfalls in the current product development approaches of SMEs to improve practices.
vii) Providing a comprehensive adoption solution from strategic to operational through practical case study and eventually developing a roadmap for RPT adoption specifically for SMEs.

1.5 Significance of the Research

The research will create a template for rapid prototyping implementation by providing a practical guide from strategic to operational level and will help to uncover the unknowns about the technology due to its emerging status. It will ensure that the selected technology finds its links with the different business functions for an effective adoption. The issue of increasing competitiveness of SMEs is one of the significant challenges faced by not only the developing countries but developed nations are also facing the similar problems. The research will help to reduce the key SMEs issues, technology related challenges and barriers in the adoption of RP technology which would have a substantial impact on the business of these small and medium companies.

Therefore, it is anticipated that this research would not only add new dimensions in the area of technology selection but will have considerable practical impact on SMEs to expand their role in the global value chain by exposing and overcoming barriers responsible for the slow diffusion of the technology. A complete system based roadmap would be a significant assistance to the companies facing difficulties in selection and adoption of the RP technology. It will also facilitate the adoption process by answering some key questions which have been considered significant barriers for adoption.

1.6 Approach of the Research

The nature of the low RP technology adoption problem demands close interaction with the industry to devise practical and relevant solutions. Literature review, collection of data by close working with industry and analysis through Analytic Hierarchy Process (AHP) are the main research methods. In the literature review, SMEs issues and challenges, previous research in the area of technology selection, rapid prototyping technology and its capabilities, strategic market and competitor analysis and decision supports system development have been investigated through journals, conference proceedings, books, newspapers articles, joining RP related blogs and associations, consulting reports from UN & OECD and through expert opinions.

The proposed research comprised of two stages, the first stage is being the development of a RP adoption framework which further consists of several other frameworks like Strategic Technology Adoption and Process Selection framework, to facilitate complete adoption. Variables, technology drivers and performance indicators were also identified during this step. Previous literature, input from academic and industry assisted in the development of initial framework.

The developed framework will be implemented in two companies, one in a developed and the other in a developing country. Design and Production Managers of both companies will be involved in the implementation process. Data will be collected for all phases of the framework for analysis. Market evaluation will be carried out by questionnaires and competitor analysis will be performed by using AHP. A framework to link technology with current and future market and micro value chain analysis of a real project will be carried out to quantify the RP impact at every stage of product development. An AHP based computerized Decision Support System will be part of an operationalization process which will be able to select the list of preferred equipment out of more than 80 commercially available RP systems, based on the 54 selection criteria.

Finally, the impact of the RP on the product development process along with weaknesses in current procedures has also been identified.

1.7 Thesis Outline

The thesis attempts to develop a practical roadmap for the adoption of RP technology. The roadmap development is based on the practical challenges faced by the SMEs, highlights the pitfalls in the current procedures and quantifies the impact of RP on business and operational strategy.

The thesis is organised into seven chapters, which are further divided into sub-sections.

i) ***Chapter 1*** describes the importance of manufacturing, role of SMEs and the challenges they are facing, the vital role of RP and its adoption through the concept of Technology Roadmapping. The chapter also presents the aims and objectives of the research and its practical significance.

ii) ***Chapter 2*** provides the basis of the research and explains the issues faced by SMEs and summarises some of the known RP methods and techniques. Previous research in the area of technology selection is explained in detail. The reasons for low adoption, its impact and inability of the previous studies are also the subject of discussion.

iii) ***Chapter 3*** presents the research methodology, its justification and reliability and validity of the data. The chapter explains the research design and operationalisation process and also details the background of the selected case studies.

iv) ***Chapter 4*** documents the development of the rapid prototyping framework and explains the operationalisation process of every single step of the framework. The tools and techniques developed for analysis are discussed in detail.

v) ***Chapter 5*** is dedicated to the implementation of the proposed research. Several tools like market analysis, competitor analysis and important performance analysis are employed for external and internal business analysis. Micro value chain analysis of a completed project is also conducted. The chapter also provides the application of the developed Decision Support System for the selection of RP technology.

vi) ***Chapter 6*** Establishes the essential links between the external environment and operational capabilities. The chapter also evaluates the selected technology, quantifies the impact of the RP on the whole business and highlights the strength of the proposed research to overcome the shortcomings in current practices.

vii) ***Chapter 7*** A summary of the findings is provided. In addition, the chapter also divulges the opportunities of future research.

2

LITERATURE REVIEW

2.1 Introduction

The massive shift of market drivers, from standardization to mass customization where the focus is on individual or small groups of customers in minimum lead and market introduction time, have entirely changed the way business was conducted in the past. This shift in paradigms requires an entirely different approach along with new strategies and technologies that have the potential to address these issues.

Details about the SMEs role and challenges, rapid prototyping technologies (RPT) and their capabilities to meet these challenges are explored in this chapter. A comprehensive review of previous researches in the area of technology selection and adoption by explaining the gaps and their unsuitability for rapid prototyping (RP) adoption, Low RP adoption issues, and challenges regarding the RPT selection is also presented. The problem regarding the operationalization and practicality is also the subject of discussion.

A detail literature review on the above mentioned impediments is presented, which provide the basis and direction for this research. The chapter also highlights the importance of technology roadmapping especially in the context of SMEs.

2.2 Small and Medium Enterprises (SMEs)

2.2.1 Description of SMEs

Different Governments, commissions and organizations defined SMEs as per their geographical location and country laws. Storey (1994) argued that there is no single, universal definition of SME. The importance of this issue has been echoed by the G20 summit in Pittsburgh 2009, which undertook to find the universal definition of SME and Micro Small & Medium Enterprises (MSME) for the sake of research, awarding grants, to develop policies and regulation for such companies (Kushnir, 2010). An overview of how the different countries around the world define SMEs is given in Table 2.1.

Table 2.1: SMEs Definition in Different Economies (C. Hall)

Country	Definition of SME	Measure
Australia	Manufacturing - less than 100 employees Services - less than 20 employees	Employment
Canada	Manufacturing less than 500 employees Services less than 50 employees	Employment
PRC	Varies with industry, usually less than 100 employees	Employment
Indonesia	Less than 100 employees	Employment
Japan	Less than 300 employees, or ¥10 million assets	Employment
	Wholesaling - less than 50 employees, ¥30 million assets	
	Retailing - less than 50 employees, ¥10 million assets	
Korea	Manufacturing - less than 300 employees Services - less than 20 employees	
	Varies. Less than RM 2.5 million and less Than 75 employees. Definitions are for SMI. Different for Bumiputera enterprises	Shareholders employees
Philippines	Less than 200 employees, P 40 million assets	Employment
Singapore	Manufacturing - less than $12 million fixed assets Services - less than 100 employees	Fixed assets employment
Chinese	Manufacturing - less than NT$ 40 m paid up	paid up capital,
Taipei	Capital and less than total assets of NT $ 120 m. In business, transport, and other services - sales of less than NT$ 40 m	Assets and sales
Thailand	Less than 200 employees for labour intensive Less than 100m Baht for capital intensive	Employment Capital
USA	Less than 500 employees	Employment

More precisely the Organisation for Economic Cooperation and Development (OECD, 2005) experts meeting in Germany explained the definition of SMEs which was recommended by the European Union Commission as an organization can be regarded as an SME if it has:

- No more than 250 employees;
- Not more than 50 million Euro turnovers. A balance sheet total of less than 43 million Euro;
- If not more than 25% of the shares of such an enterprise are in the ownership of another enterprise.

2.2.2 Critical Role of SMEs

The strategic importance of SMEs in the development of the economy is widely accepted in developing and developed countries (Abdullah[a], 2000). The SMEs play a pivotal role in the development of any country. The UK economy consists of 99% SMEs, so out of 4.8 million UK businesses, less than 1% are large corporations i.e. Corporations with over 250 employees (Rowe, 2008). The share of SME employment accounted for 70% of total employment and the product share for over 46% in South Korea (Lee, 2000). In Malaysia, SMEs accounted for about 48% of the manufacturing sector (Abdullah[b], 2000). According to the Australian Government Small Business Statistics there were 2051085 actively trading businesses in Australia as at June, 2009 (DIISR, 2011). Figure 2.1 shows around 96% were small business; 4% were medium sized and less than 1% was large business.

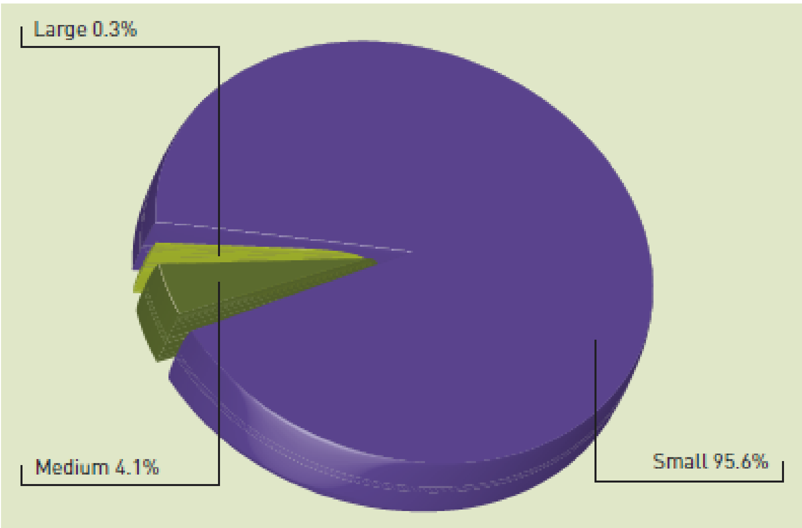


Figure 2.1: Australia Industry Statistics (DIISR, 2011, p. 8)

2.3 SMEs Issues and Challenges

2.3.1 Management Issues

It is imperative to consider the unfolding dimensions of the SME infrastructure before moving into any technology related issues. The main reason is that any suggested solution may lose its effectiveness if made without considering the environment in which it is going to be implemented. This is particularly beneficial for SMEs as they differ from that of large companies in many respects and any solution designed for large companies may not fit the needs of the small companies. (Ahmad et al., 2008) pointed out the reasons for this as:

i) Education levels of employees at SMEs are comparatively low.
ii) Most managerial positions are acquired based on experience, and they lack professional qualifications.
iii) R&D culture is not common due to financial constraints.

Another big issue that hampers new solutions is the resistance to change factor, which is extraordinarily strong in SMEs. Technologies and solutions adopted by their predecessors are considered to be safe and reliable, which makes the new adoptions devilishly difficult and demands powerful and convincing solutions. In Malaysia, management abilities, R&D and technology capability in particular are constraints on innovation and high value added activities in the small and medium sector (Peter et al., 2000). SMEs in Korea are economically weak units facing lack of technical competitiveness, money, skilled labour force, management and market awareness (Abdullah[b], 2000). Management problems in SMEs are largely due to the fact that many of their entrepreneurs lack high levels of education & professional training and they perform poorly in many areas of production and quality control (Abdullah[a], 2000).

2.3.2 Technical Challenges & Role of RP

Emerging technologies and markets present tremendous challenges and opportunities to firms seeking a competitive edge from them (Thukral et al., 2008). With the increased complexity of products, the product life cycle and time to market are shortening. In this challenging scenario, the capacity building of SMEs can play a vital role particularly during the product development cycle as the process can be regarded as a gateway to international markets. To ensure long term success, the manufacturers are required to concentrate on both markets and technology (IEA, 2009). Design and development of the products are one of the critical activities, which largely determine the success and status of the company in the market. A typical product development cycle as shown in Figure 2.2 indicates that product prototyping is at the heart of the complete cycle. This is a gateway to the customer and manufacturing at the initial stage and requires several iterations before the formal manufacturing can be started. A greater control and success at this stage ensures not only a satisfied customer with all the requirements incorporated but also reduces reworks and time to market at later stages. RP technology can assist in the compression of time with complete customer satisfaction at this stage which ultimately can increases the ability of the firm to maintain a reasonable market share.

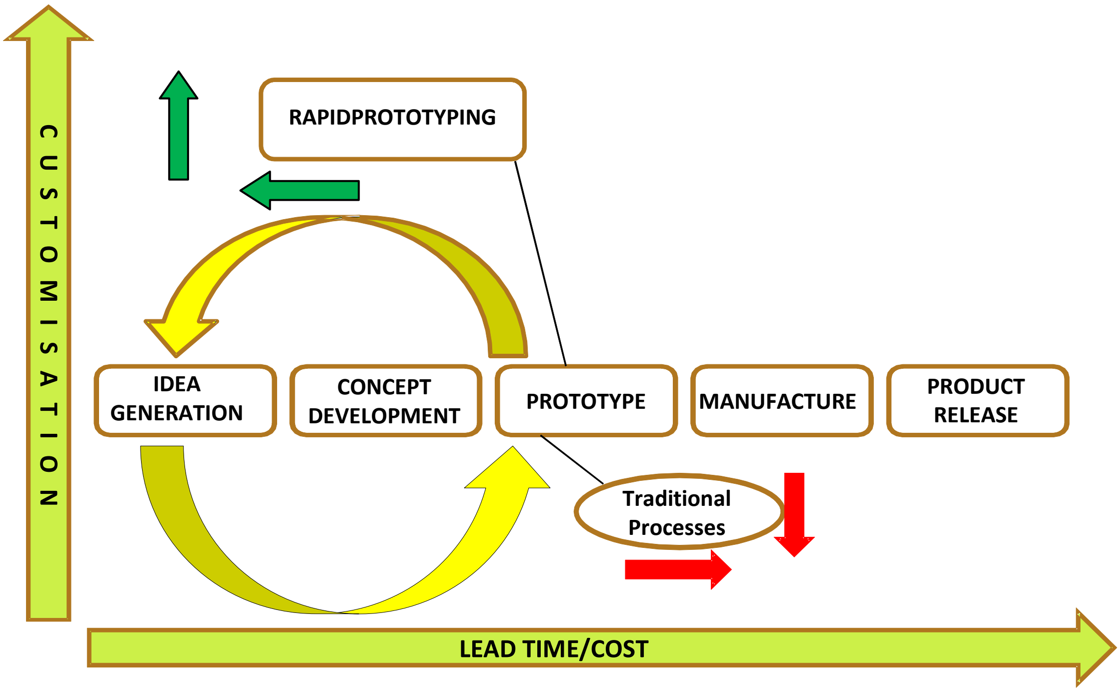


Figure 2.2: Role of RP in Product Development Cycle (Ahmad et al., 2012)

Reliance on the traditional methods and inability of the small firms to recognize the benefits offered by the technology like RP is holding this sector back from playing a critical role in world markets, where several firms are worried about losing business with multinational corporations. Many large companies still import their components, rather than purchase from local SMEs supplies. The main reason is the high price and low quality of the locally produced components (Abdullah[a], 2000). A recent UN document stresses that production capacities should be placed at the heart of National Policies. There are a number of obstacles faced by firms which limit their growth and relations with the global value chain, and one of them is the ability of SMEs to compete (UNCTAD, 2006). The Institute of Engineers Australia indicates that the long terms success of manufacturing requires attention on both markets and technology (IEA, 2009). Focus on markets and improving the production capabilities are the areas where SMEs require urgent attention. Emerging technologies can play a considerable role in this regard. Rapid Prototyping (RP) Technologies have tremendous potential to address these challenges. (Kidd, 1997) suggested that RP technology is not for large firms only; it also offers tremendous potential for SMEs to pursue and create new opportunities. Despite great advantages of the technology, only a small proportion of the SMEs currently understand the need and opportunities that RP presents.

The next section systematically defines technology first and then highlights the issues behind the low adoption.

2.4 Rapid Prototyping Technology (RPT)

Prototyping finds its origin in 1603, from the Greek word prototypon “a first or primitive form”, protos “first” + typos “impression”. Rapid prototyping is an Additive Manufacturing (AM) technology as opposed to its predecessor CNC which is a subtractive one, which produces parts layer upon layer after getting input from 3D design software. Since the inception of Rapid Prototyping, several definitions of the terminologies were used but lack any standard meaning. American Society of Testing and Materials (ASTM) produced a standard Designation: F2792-12a document published in March, 2012. The F42 committee on Additive Manufacturing defined Additive Manufacturing (AM) as “*A process of joining materials to make objects from 3D model data, usually layer upon layer as opposed to subtractive manufacturing methodologies”*.

Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and free form fabrication” (ASTM, 2012)

All these synonyms have been used interchangeably in the literature, but they stand for the same technology.

2.5 Rapid Prototyping Process

The basic RP process consists of four stages as shown in Figure 2.3. The Design stage is the creation of a solid model on 3D commercial software like AutoCAD, SolidWorks etc. Once a solid model is generated in CAD, the developed model is converted into a STL or IGES format depending on the software or the technology used.

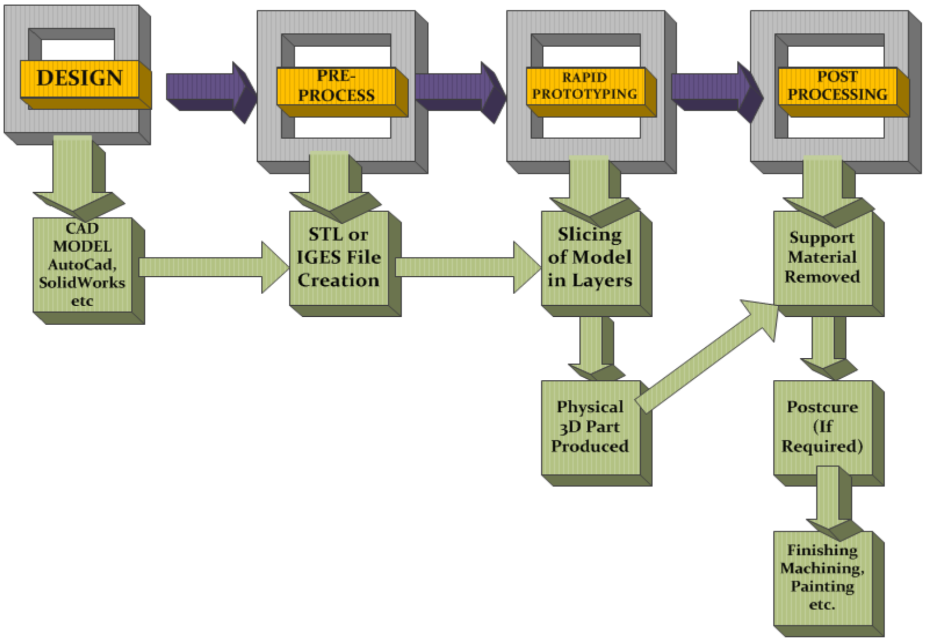
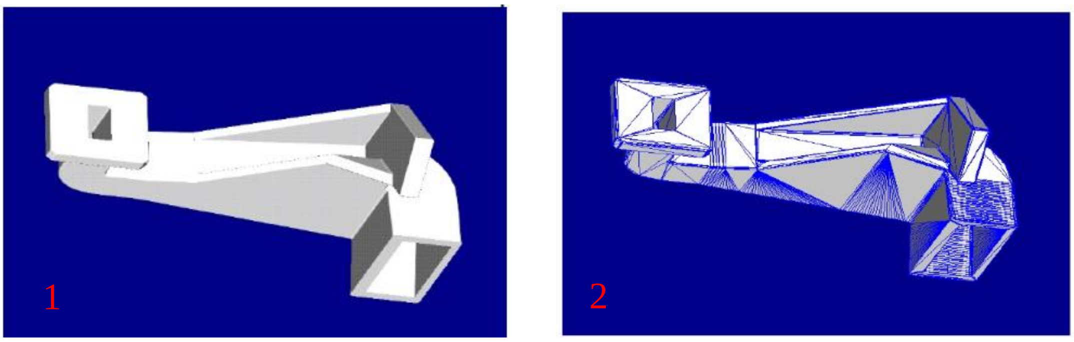


Figure 2.3: Schematic of RP Process

The STL converts the CAD into a computerized format at the Pre-Process stage which approximates its surface into small triangles. The STL file consists of the X, Y, Z coordinates of the three vertices of each triangle. Figure 2.4 shows a comparison of a CAD and STL file of the original design.

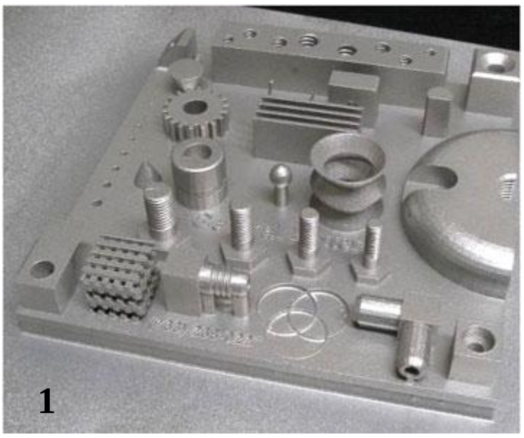


1) CAD Model 2) Conversion into STL. File

Figure 2.4: CAD and STL Model Comparison (Vivekanand, 2012)

The STL file is sent to the RP equipment at the rapid prototyping stage, which first slices the model into a number of layers from 0.01mm to 0.7mm thick depending on the type of technology used[1]. The RP machine then builds the designed model one layer at a time and the process continues layer by layer until a complete model is built. Several types of materials like polymers, paper, plastic and metal are available. The selection of material is based on the intended use and type of RP technology.

The post processing stage is the removal of the physical part from the machine. Some photosensitive materials need a cure before it can be used for the intended purpose. Support structures are required to be removed if generated during the design or prototyping process. Some finishing processes are also possible like sanding, machining or painting which largely depends on the technology or equipment selected as different technologies offer different materials with unique material characteristics. The type of post processing is based on the material selected and capabilities of the RP equipment. Figure 2.5 shows some parts produced directly by the EOS (Germany) 3D printer.



1) Benchmark test geometry in EOS Stainless Steel 17-4.

2) Spinal implants built in EOS Titanium Ti64

Figure 2.5: Parts Produced by EOS 3D Printer (MorrisTechnologies)

2.6 Rapid Prototyping Techniques

Most of the commercially available RP systems are based on one technique out of six available. These techniques are:

[1] The programme also creates structures to support the model. These supports are useful for delicate features like overhangs, thin walls etc.

2.6.1 Stereolithography (SLA)

The term Stereolithography surfaced in 1986 when Charles (Chuck) W. Hull patented a procedure and technology for producing solid parts. The technique forms a 3D model from a liquid ultraviolet curable photopolymer resin which solidifies when open to ultraviolet light.

2.6.2 Laminated Object Manufacturing (LOM)

The material used in this case is laminated paper with heat-activated glue. The system consists of the feed roller which advances the sheet on the platform. A heated roller applies pressure to bond different sheets together. A laser is used to cut the outlines of the parts. After every successful cut, the platform lowers down by a distance equal to the thickness of sheet (usually 50-500µm) and the process continues until a final part is produced.

2.6.3 Selective Laser Sintering (SLS)

SLS process uses a high power CO_2 laser, to fuse small particles of powdered materials such as plastic, metal, glass or ceramic into required three dimensional models. The laser outlines the cross section based on the design and diffuses it together on a powdered bed; the platform then lowers down by one layer of thickness. A new layer of material is then applied, and the process continues until the final part is produced. Excess powder material acts as supporting material during the post building process.

2.6.4 Fused Deposition Modelling (FDM)

Thermoplastic Filaments from a coil provide material to a heated nozzle, which is then extruded from the tip. The nozzle moves in the X and Y direction and deposits small amounts of thermoplastic beads on a platform, which solidifies immediately due to the low temperature of the platform. This forms the first layer of the desired model. The process continues layer by layer until a complete model is developed. Support material is also supplied through the same nozzle to provide supports to weaker areas.

2.6.5 Ink-Jet Printing

Developed at Massachusetts Institute of Technology (MIT), it employs the same principle as of 2D printing in which ink is deposited on the paper through a jet but uses a thermoplastic or wax material in melted form. The printing head deposits the material droplets into the form of desired cross section while moving across the bed of powder, the material then solidifies; the platform lowers down and another layer of material is spread across the previous one. The process continues until the final shape is achieved; the unbound material provides support to the weak or over hanging areas.

2.7 Low RP Adoption Challenge & Causes

Despite the immense potential RP has especially on the product development cycle, a large proportion of SMEs are still not reaping the benefits. Styles (2012) insisted that worryingly only 10% of small companies are using RP technology. A survey of 262 UK companies exposed that 85% of them never used this technology. Lack of cognizance of what this technology can do or what effect it can have on the business is making RP irrelevant to them (Grenada, 2002). Kidd argued that RP technology proposes incredible potential for SMEs to search and is not only for large companies (Kidd, 1997). The general consensus is that less than 20% of the design and product development departments use rapid prototyping and in manufacturing the extent of use is even less (Grimm, 2004). This is worrying that engineers and production departments are oblivious about rapid prototyping which has dramatically changed the way of conducting business (Laar, 2007). Despite the capacity of the RP technology to address the challenges which the SMEs are facing like limited design and manufacturing ability, still only a small percentage of the industry is in use of this technology (Ahmad et al., 2009).

The low adoption challenge consists of several issues. These issues include understanding drivers of the technology, selection of the right technology and availability of practical solutions. These problems will be explained in the coming section, and a summary of the previous researches will also be a part of the discussion to show how they are not effective in the case of RPT adoption.

2.7.1 Obliviousness of RP Technology and its Impact

Understanding the technology and its impact on business operation and competitive position are an essential and critical part of any technology related initiatives. Technology diffusion is composed of many different decisions, which are the outcome of comparing uncertain advantages of the new technology with the uncertain adoption cost and understanding of these factors is essential (Hall & Beethika, 2003).

According to some authors, Narain and Sarkis (2006), the most significant point is the high capital investment required for initial RP purchase, due to which the SMEs are not able to afford this technology. This argument was true during the inception of technology, when the introduction costs were high and truly were out of reach for such small companies. This impression continued to grow even though the cheapest 3D printer is now available for around $7000 (Asiga, 2013). This is now much less compared to the introductory prices which were around $100,000. Despite the low investment cost, technology is not getting as much attention at the SMEs level in comparison to its ability to solve their issues. This proves that the cost is not the only concern; the problem is required to be analysed from a different perspective. Terry Wohler in his famous Wohler's report (Wohlers, 2002) pointed out that price is not the only issue, but this complex problem has many layers, which demands detailed analyses and it can be simply defined as,

"WIIFM ÷ WWIHTD where

WIIFM = What's in it for me

WWIHID = What will I have to do"

Every single "W" needs an independent and comprehensive answer. If a company or individual is convinced by the RP technology, then the next question comes "what I need to do"? This single question is comprised of several other issues which are the topic of discussion in the coming section.

Laar (2007) expressed concerns that technical departments are still ignorant of the technology which is disturbing especially when the technology has transformed the production methods.

2.7.2 Issues of Process Selection

The increasing number of RP systems available in markets with different capabilities has made the selection of the right RP system very complicated. There are large numbers of systems available worldwide with all different prices, materials and technical capabilities like surface finish, accuracy etc. Selection of the right kind of technology has a critical impact on the business operations and competitiveness of a company. When designers are encountered with the throng of product development criteria and business requirements, which must be aligned with the selected technology, the task becomes very difficult and even more complicated in the case of SMEs due to the low education and lack of R&D, mentioned in previous sections. A large percentage of SMEs are still dependent on subtractive procedures like CNC for the product development process. This process has limited capabilities when the product is complex or time to market issues are dominant. It limits the design capabilities of the company by reducing its capacity to cater to the variety of customer requirements, ending up with the shrinking chunk of market share. Grimm (2005) highlighted the critical issue of RP technology selection as,

"*Selecting the right prototyping process can be difficult, but it is critical to the success of your product development process. Picking a solution requires experience, information and understanding of a broad set of processes, techniques and technologies. This is a skill that few possess, when expanding the scope to include all additive and subtractive methods".*

Brown and associates (Brown & Stier, 2002) highlighted the fact that analysing all the alternatives is a complex task, particularly for those who have never dealt with a RP system. Wohlers (2002) reported that rapid developments in RP has multiplied the earnestness in demands of new technology evaluation to make a decision regarding if they are required and when they should be implemented. Grenada (2002) commended that there is a lack of knowledge regarding the capabilities of additive and subtractive technologies, which should be analysed by the prospective user for any particular applications. Destefani (2005) highlighted similar issues in that right RP selection is equally hard for product development. The selected method has an enormous impact on business operations and time to market, and there is no clear answer regarding which is the optimum technology.

2.7.3 Operationalisation Issues:

An effective technology adoption is a complex task, which needs an enormous amount of information about the external environment and inside operation of the organization. Understanding of the technology drivers, their ability to influence current policies, business procedures and understanding of complex technical aspects are essential parameters for any technology related initiatives.

Effective Technology Adoption (ETA) describes a complete mechanism which ensures that the selected technology manifests itself into all business functions. OECD (1988) explained a similar process called Constructive Technology Assessment (CTA), the purpose of which was to minimize erroneous investment decisions and mistakes.

RP technology is an emerging technology surrounded by myths, lack of understanding about its capabilities, qualms about what impact it can have on the business operations and which technology fits with their requirements. The situation gets worse and complicated when the potential adopter of the technology is an SME with many issues, which have been discussed in section 2.3. The result is either reliance on traditional procedures or the adoption of a wrong technology. Kidd (1997) argued that RP technology offers new strategies, procedures and approaches and failure to ascertain these capabilities ends up with wrong investment decisions and lost opportunities. Grimm (2006) mentioned that “Industry has failed to recognize many of the opportunities that Direct Digital Manufacturing offers”. Ordoobadi and Mulvaney (2001) explained the issue of operationalisation as “Many times the selection model would make a few suggestions and then leave the generation of the benefits up to the decision maker. This leaves no formal methods for educating or reminding the decision maker of what kind of benefits exist with these technologies”.

The above situation stresses the need for an integrated solution which is practical in nature and is capable of providing a comprehensive adoption guide from strategic and operational level. Development of an adoption framework only is not enough to address this complicated challenge unless the complete procedures are in place to bring this into reality.

2.8 RP Technology Roadmapping (TRM) for SMEs

The new or emerging technologies like RP have unusually slow diffusion processes. The uncertainties surrounding the technology, lack of understanding regarding the advantages or opportunities which can be obtained, recognizing the changing market dynamics, matching it with the technology drivers and justifying the adoption based on both cost and operational parameters is a very complicated and tricky task. The information overloads and a lack of practical, relevant and easy solutions leave no way other than maintaining status quo at SMEs. If one dares to use the technology, the wrong selection or underutilization sends a false signal to the wider SME community, ending up even a step backwards towards the adoption.

Unavailability of complete adoption solutions along with resistance to change works together where the end results are inclined towards the continuous use of the old and traditional procedures and technologies. Technology Roadmapping (TRM) is a powerful tool which has significant potential to overcome these issues and to provide solutions which are applied.

Koen (1997) also described the obstacles in the area of technology planning indicating that this is a path of unexplored customer requirements and competitor competencies, and many begin with no clue of the difficulties and alternative trails. The result of which is the deviation of expertise in the wrong direction and suggests that the mapping process is capable of providing a graphical direction for the technology journey. Engineer Australia Members identified Technology Roadmaps as the most crucial factor to the development of successful National Manufacturing Policy (IEA, 2009).

Technology Roadmaps can play a key and vital role for the adoption of RP technology, which is still emerging. This can be done by devising a complete and practical adoption solution from strategic to operational level. The importance of such roadmaps increases several times when the capabilities of the potential company are already in question and not much information is available about the technology.

2.9 Existing Research related to Technology Selection & Assessment

Technology Assessment is a relatively new emerging area, which found its roots in the 1960s in USA when technology intensely started to modify the way of life. Despite its emergence over the past four decades, there is still a dire need to find more efficient methods (Tran & Daim, 2008). Technology selection is concerned with the selection of the best technology among a number of alternatives, leading to complex decision making due to increased complexity and range (Rudder et al., 2008). Selection of technology on the basis of technical parameters can limit the effectiveness of adoption as the selected technology will have a direct impact on the business functions. Therefore, the link between technology and business functions must be considered carefully before selecting a particular adoption. The situation poses more difficulties when the decision makers find themselves unable to integrate the theory and practice because they lack the ability to match their exclusive problem with the applicable theory to devise an effective solution (Tate & Nordlund, 1996). To ease the situation and after linking extensive literature with real issues, a new terminology emerged during the research called "Effective Technology Adoption (ETA)". The main aim of any ETA plan is to ensure that technology links itself with all business operations. A business is constituted of different functions, and an improvement or boost in business requires a boost in each single function. As these functions are somewhat technology dependent, this stresses the need for strong links between them. The minimum charter of any ETA plan can be summarized as:

i) Complete and accurate understanding of internal and external drivers along with competitor's capabilities and complete picture of global trends.

ii) A precise measure of internal capabilities, to explore and highlight the mismatches between internal capabilities and external demands and also to demonstrate a technology-strategy link.

iii) Selection of the right equipment, which is capable of meeting strategic, financial and operational requirements of the particular company.

iv) A complete guide, equipped with appropriate tools and techniques to address the above mentioned issues. The guide should be practical in nature, capable of providing a complete mechanism for implementation.

Voss (1988) echoed the same idea by outlining an effective technology adoption plan, which should consist of three phases mentioned in Figure 2.6.

Figure 2.6: Voss Life Cycle Model of Implementation Process (Voss, 1988)

The charter of ETA emerged after the concerns raised by experts in the area of manufacturing strategy and technology assessment. Manufacturing strategy is concerned with product planning, resources deployment and is an area of increasing concern which has been ignored in the past and has commonly been considered as a poor link with other vital functions like finance and marketing (Cil & Erven, 1998).

Grieves (2006) raised concerns regarding the lack of availability of complete adoption solutions and highlights that most implementations have involved point solutions, which only provides limited benefits of Direct Digital Manufacturing, making it less effective as compared to integrated solutions. Huang and Mak (1999) in their study of 100 British Manufacturing companies explains that poor management and readiness for change often ends up with failure of the selected technology and one reason is credited towards the incapacity of the organization to recognize the broader relationship of technology to the business. Naik and Chakravarty (1992) concluded “It is clear from published literature and other sources that new technology justification studies have failed to include appropriately all relevant attributes of the system in such analysis. Poorly designed systems can lead to disaster and unfortunately very little prior information is available”.

Voss (1988) also expressed his concern regarding the absence of study of the total implementation process from Academics. The Department of Business Enterprises and Regulatory Reform (BERR) UK stated “The cost of demonstrating that a new technology or production process is viable can be a significant barrier to investment in the development of new product, especially for smaller manufacturers” (BERR, 2008).

Practical implementation entails practical tools and techniques to support management decisions, need processes to solve particular business issue and also requires conceptual frameworks along-with practical tools to guide technology management (Phaal et al., 2006). This argument also endorses point four of the ETA charter with a specific emphasis on practicality.

The next section analyses in detail the previous research in the area of technology management, their ability to address the specific RP adoption related issues by keeping in view the distinctive characteristics of SMEs and their capabilities to meet the ETA charter. Problems in selecting the RP technology and previous studies regarding RP selection is also the subject of discussion.

Technology selection is related to the selection of the best technology amongst those available, whereas adoption is the assortment of external and internal business functions. According to Chan et al. (2000) the selection and validation procedures demand investigation of the large number of economic and analytical factors. The change in the external markets or customer requirements generally triggers the replacement of the older technologies or introduction of the new technology to meet or address these changes which can also be regarded as “Push” for technological change.

Most of the previous research in the area of Technology Management or Assessment is based on Advanced Manufacturing Technologies. AMTs include Computer-aided design/computer-aided manufacturing, Computer-aided process planning (CAPP), Flexible Manufacturing Systems (FMS) and Flexible Assembly Systems (FAS) (Chen & Small, 1993). Due to the high initial capital cost involved, these systems are meant for large companies, and are focused on the financial justification of the selected technology or traditional investment justification criteria (Shehabuddeen et al., 2006). Another phenomenon occurs where gradual change in the market and customer demands do not trigger any technology upgrade or new adoption, and despite technology advancements the diffusion of technology still remains in inverse mode, thus increasing the gaps and limiting the capability of the company to respond to external changes and requirements.

The ultimate result is decreasing competitiveness and losing market share. This situation demands push systems, which are practical, integrated and unique for the technology under consideration. Small and Yasin (1997) also stressed upon the studies which focus only on selected technology.

Chen & Small Integrated Planning Model

Chen and Small (1993) proposed an integrated planning model for the implementation of AMTs. The model shown in Figure 2.7 was developed to minimize risk in implementation due to the high cost involved and on the supposition that managerial problems from planning to implementation are key barriers for adoption. The model is based on the three phases of implementation. The first is the pre-installation phase whereas second and third phases are installation and post installation phases. The first step of the proposed framework highlights the building elements of the implementation process, initiating from strategic planning, which should be capable of taking a broad view of both business and technology and should provide the direction of every sub unit towards the business strategy. The second step emphasizes the identification of the product range and identification of technology to manufacture these products.

(1)	Linking manufacturing to business strategy
(2)	Coordinating marketing and manufacturing strategy
(3)	Developing a long-term automation strategy
(4)	Monitoring AMT being used in the core industry
(5)	Matching capabilities of AMT to benefits expected by the Plant
(6)	Ensuring compatibility of AMT with existing production Systems
(7)	Ensuring vendor commitment during and after installation
(8)	Obtaining the services of knowledgeable AMT consultants
(9)	Hiring or retaining AMT experts on plant staff
(10)	Having multi-skilled production workers
(11)	Communicating the likely impact of the AMT to all plant workers
(12)	Emphasizing team-work and group activities
(13)	Pre-installation training of all project participants
(14)	Considering likely impacts on customers
(15)	Considering likely impacts on suppliers
(16)	Establishing multi-disciplinary planning teams
(17)	Establishing multi-disciplinary implementation teams
(18)	Top management involvement
(19)	Choosing knowledgeable project leaders
(20)	Financial investment evaluation prior to installation
(21)	Strategic investment evaluation prior to installation
(22)	Developing system performance measures prior to installation

Figure 2.7: Chen & Small Integrated Planning Model (1993)

The third step suggests the importance of monitoring the performance of the technology to improve their market position. The model also highlights the importance of linking technology with marketing and its relation with the external environment. After the initial analysis, the model suggests the cost justification of the technology. The authors developed a questionnaire on the activities mentioned in Figure 2.7 to get information regarding how much effort is spent on each criterion by the company. The model links technology with strategy but is heavily focused to minimise risks due to the high cost of automation. Most of the steps mentioned are irrelevant in the case of RP adoption.

Coates Technology Assessment Framework for Developing Countries

Coats (1998) proposed technology Assessment guidelines to assist Governments of developing countries for the management of new technologies. The aim of which was to anticipate and consider the health, safety and environmental impact of new technologies into the developing countries. It provides systematic guidance on the possible impact of the new technologies but does not provide any detail about how to evaluate any particular technology alternative for the said purpose but was to create awareness amongst the potential adopters.

The framework was developed on a fundamental assumption that highly capable people have strong concern regarding national development but they do not have trainings to evaluate and understand the potential impact of new technologies.

Figure 2.8 shows the schematic of the technology assessment model presented by Coates. The model starts with the justification or rationale of the proposed technology. Technology characteristics in organisational contexts and evaluation of alternatives constitute the second and the third part of the framework. Fourth and fifth steps of the framework suggest the evaluation of the state of society and the identification of relative stakeholders. The framework is designed for experienced users, who already have deep knowledge regarding the technology and are able to identify its impact. Several factors like state of society are irrelevant in case of RP adoption.

Identification of possible consequences and analysis are the subject of the next three steps, whereas the last two steps address the determination of respective decision and policy making, ending up with the conclusion and recommendations.

Ordoobadi & Mulvaney Justification Tool for AMTs

Ordoobadi and Mulvaney (2001) developed a justification tool for selection of AMTs based on system wide analysis. The basis of this development was the inability of traditional economic analysis procedures to justify the high cost of AMTs involved.

A new process called the system wide benefit value analysis was introduced, where the user first performed economic analysis, and if the cost is not defensible then the gap between the actual rate of return and the desired rate is calculated, and through a defined procedure, the value of system wide benefit is calculated to find if it was reasonable enough to fill the gap. The tool was developed on an underlying theory that many advantages associated with these technologies are qualitative in nature and undeniably have an impact on operations and business.

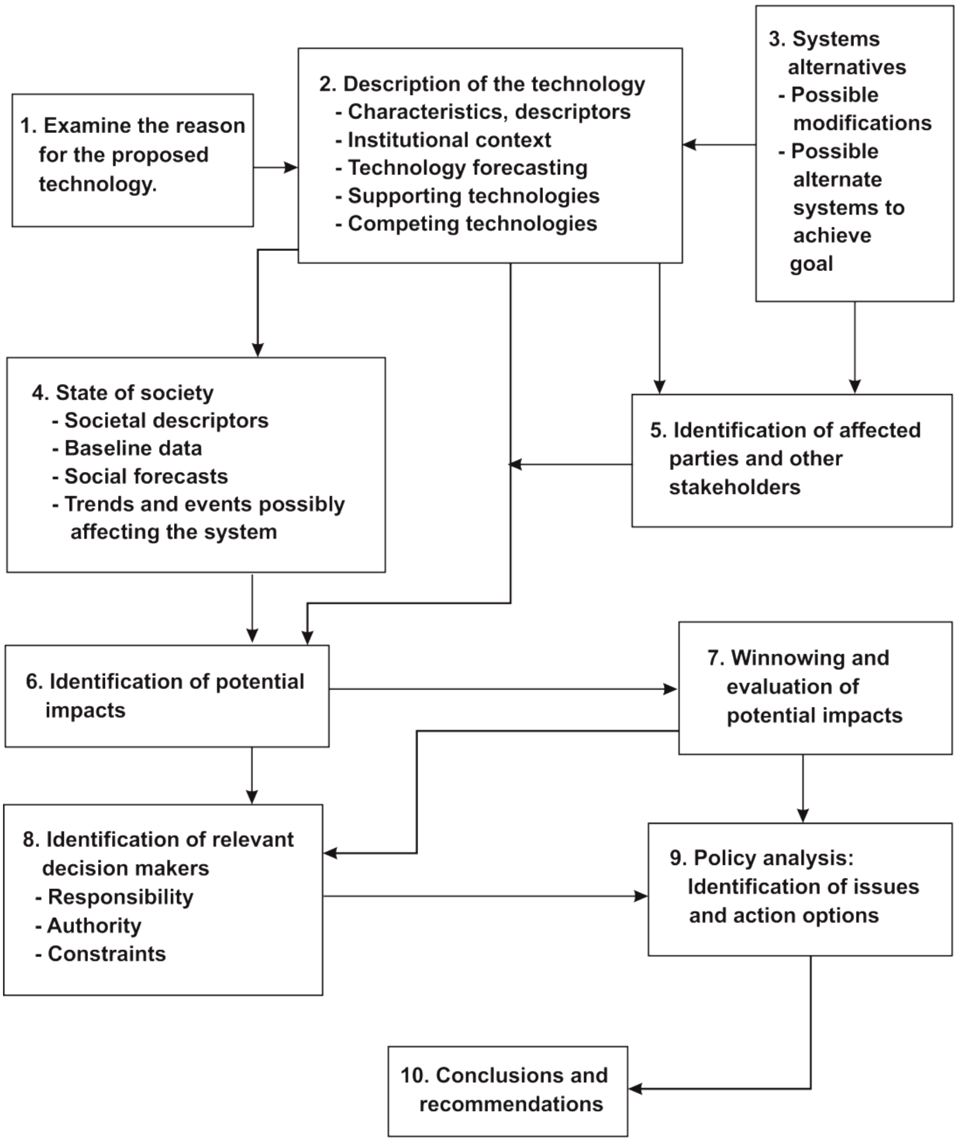


Figure 2.8: Coats Technology Assessment Framework for Developing Countries (1998)

People are often not aware about the existence of such benefits, but these must be part of any formal evaluation procedure.

The justification tool comprises of two steps, first was the development of the model of system wide benefits required to consider during AMT investment decision. The second step is related to the methodology development for AMTs evaluation as shown in Figure 2.9, which used the previous developed model to assist to find the value of the benefits associated with the specific technology. The first step of evaluation of AMT used traditional cost justification techniques like internal rate of return (IRP) and NPV and payback period method. The framework was based on a long list of advantages due to the high degree of automation involved in AMTs and was not suitable in RP adoption.

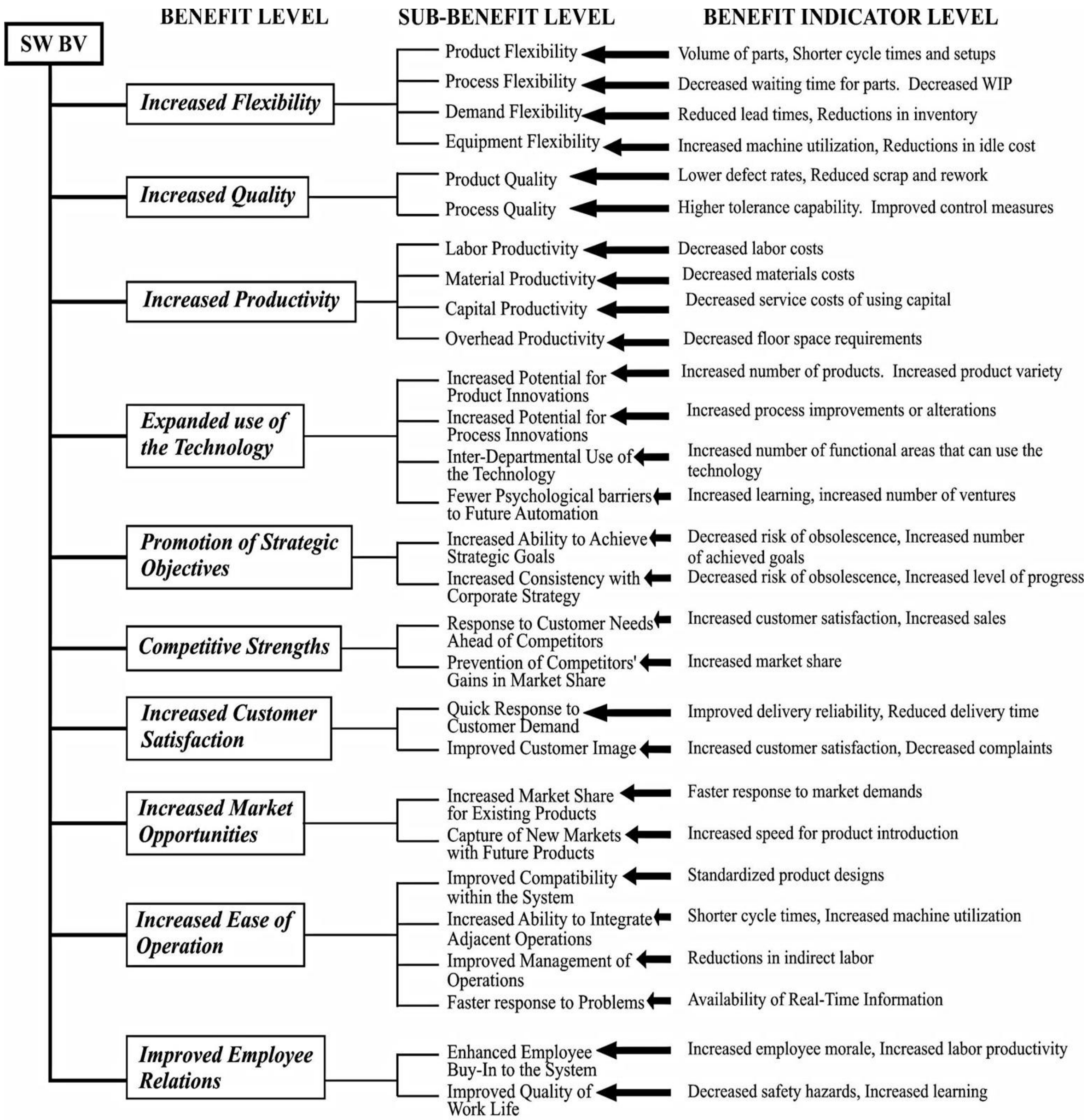


Figure 2.9: Ordoobadi & Mulvaney Justification Tool for AMTS (2001)

Kengpol & O'Brien Decision Support Tool for the Selection of Advanced Technology

Kengpol and O'Brien (2001) proposed a decision support tool to evaluate the value of investment in Time Compression Technologies (TCTs) for the sake of rapid product development. The tool was based on the necessity of an integrated model which can combine models for quantifying the impact of value of development time reduction, in other words Cost/Benefit Analysis, and measure of effectiveness of the decision making process which ultimately can lead towards the likelihood of the product success. The proposed model is shown in Figure 2.10.

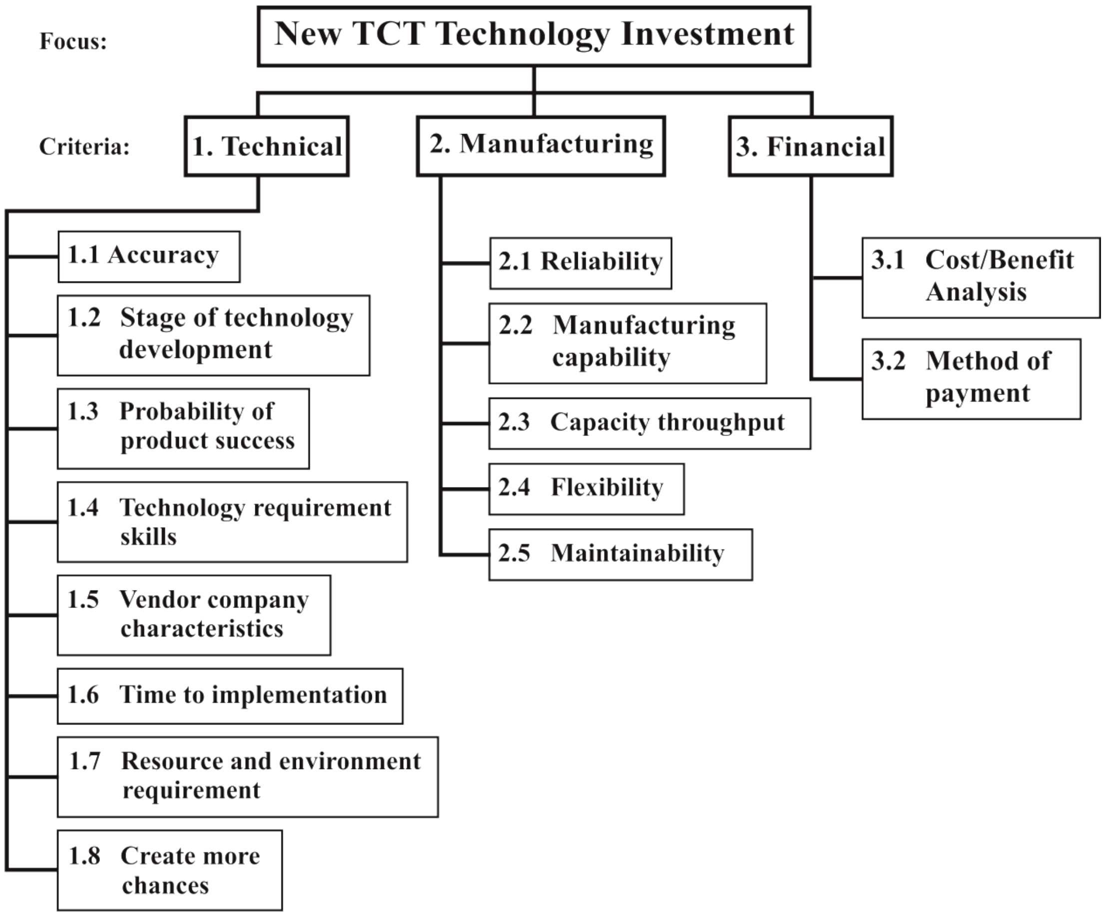


Figure 2.10: Kengpol & O'Brien Decision Support Tool (2001)

The research was focused on Cost/Benefit Analysis of the new technology by quantifying the financial impact of any delay in production introduction. The authors first developed a Neutraline Profitability Model which was an anticipated cash flow and showed the cumulative profit before tax over the period of five years when the product was introduced on time. It then showed a Profitability Model when a product launch was delayed by six months, resulting in a 23.5% decline in profit from Neutraline which was the cumulative profit before tax for the entire life of the product. It also depicts the results when the product was released on time, but with a development cost of over 50% of budget.

The research was primarily associated with financial impacts of product launch times but does not actually highlight the product development process and constituents of delays or early introduction. The model does not grasp the external environment issues and also does not consider the internal operational evaluation. It also does not suggest the technology selection procedures which makes it unsuitable for RP adoption due to its specific adoption issues.

Shehabuddin, Probert & Phaal Technology Selection Framework

Shehabuddeen et al. (2006) suggested a technology selection model with a specific focus on packaged technology, the technology which does not require R&D after acquisition. The model emerged after realization of the fact that the majority of the previous studies in the area of technology selection are inclined towards the AMTs adoption and were more concerned about the financial justification. The authors also expressed their concerns on the practicality of the previous models and explained their shortfalls in practical application cases. They also declared that the real challenge is in bringing the theory into practice.

The framework was based on two key elements “requirement criteria and adoption criteria”. It also introduced the concept of primary and secondary layer filters. The primary filter eradicates the technologies which do not fulfil the must-have demands whereas the secondary filters facilitate the technology which possesses desirable but non-critical criteria. Whereas the requirement filter was further divided into technical, financial and external pressure sub-filters as shown in Figure 2.11.

The adoption filter is further divided into five sub-filters. A computer tool was also developed and technical options positioned where users can rank them on a scale of maximum 100 points.

The framework also considers internal and external agents, which can influence the decision making. The internal agents are production, finance and human resource whereas external agents include customer, technology supplier, competitors and regulatory bodies. Ranking of the technical choices indicates that the user should be capable of understanding the features and abilities of the potential technology. The model is generic in nature and it is expected that the user understands the technology and its impact. Specific RP evaluation, which is a critical issue, is not a part of the framework which makes it least applicable for specific RP adoption.

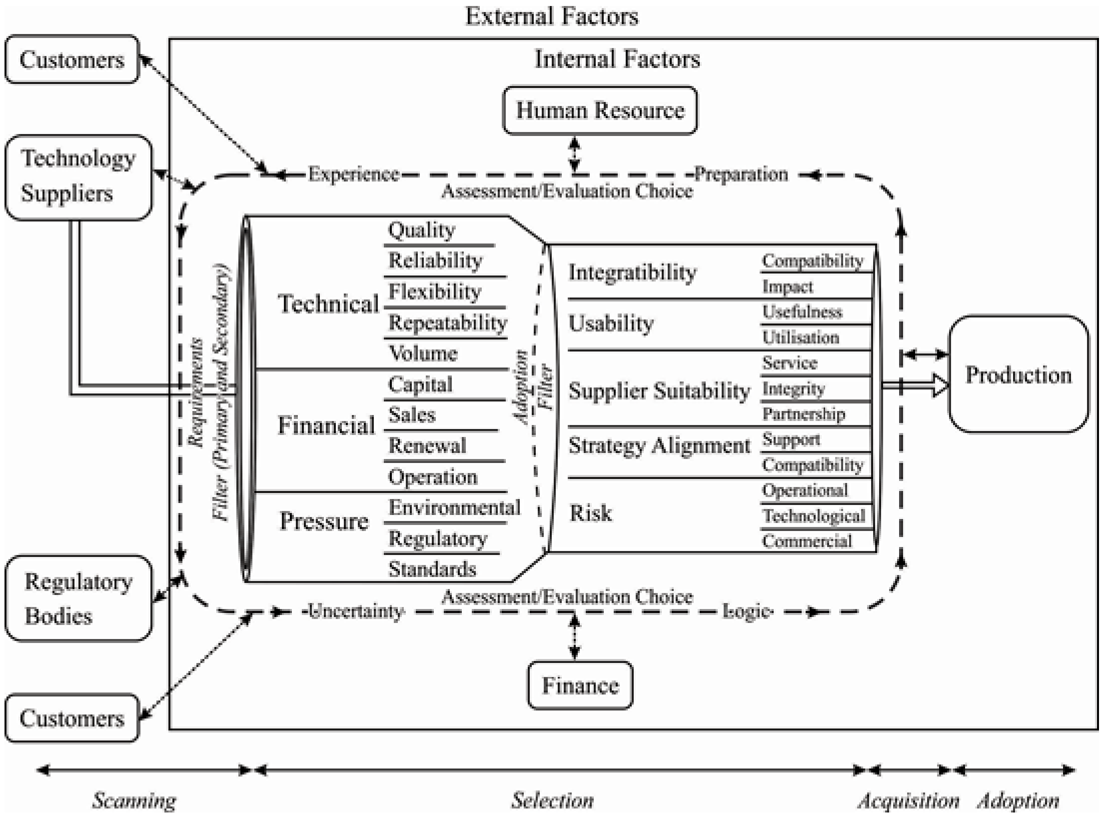


Figure 2.11: Shehabuddeen, Probert & Phaal Technology Selection Framework (2006)

Ruder, Pretorius and Maharaj Technology Selection Model

Rudder et al. (2008) developed a Technology Selection Model for the Telecommunication Industry in developing countries. The purpose of the suggested model was to assist the South African Telecom Sector in the selection of technology for the mobile wireless industry. The authors explained the importance of the technology selection for the business and highlighted the difficulties faced by the business in the selection of the right technology. The first phase of the model started with the identification of decision makers and stakeholders as shown in Table 2.2.

The step outlines the importance of group decision making processes to ensure the responsibilities and roles are assigned, clear and documented to avoid any confusion. The second phase focuses on the identification of existing competencies or the technologies the organisation currently own. The purpose of new technology in line with the products or services, the company offers, should be taken into account. The third phase concerns the agenda formation to take a decision regarding the current position and where it needs to move with the new technology.

Table 2.2: Rudder, Pretorious & Maharaj Technology Selection Framework (2008)

Inputs	Phases of the Process	Outputs
• List of relevant and affected participants	1) Identification of decision makers and stakeholders	• A list of the participants for the group that will make the decision • A list of participants that will be affected by the decision • A list of any other participants
• The purpose and task of the new technology • The business goals and strategy of the organization	2) Identification of existing core competencies	• A list of existing core competencies and technologies • Linkages between core competencies and the competitive advantage of the organization • Trends in the industry
• List of existing core competencies and technologies • Trends in the industry	3) Establishment of the agenda and strategy	• Redefined business strategy • Requirements of the new technology
• The knowledge of experts • Planned application areas and tasks for the technology • Requirements of the organization	4) Identification of alternative technologies	• A list of possible technologies to be acquired • The characteristics of all the technology alternatives
• Business goals of the organization • Expert's knowledge and opinions about the criteria to be selected	5) Identification of selection criteria	• List of criteria • Criteria classified into categories
• Experts knowledge and opinions • Business goals of the organization	6) Determination of utility and weights for chosen criteria	• List of criteria • Criteria classified into categories
• Categorized criteria • Criteria weights and utility functions	7) Assessment of alternative technologies	• List of ranked technologies • Technology selection decision

The fourth phase proposes to develop a list of technologies which can be utilised to achieve the goal set in the previous step. The next step is concerned with the selection criteria identifications. This phase demands the expert's knowledge that can be utilized in the selection process. The next two phases are the determination of weights of the chosen criteria and selection of technology based on that.

The framework was applied in two case studies but the analysis only gives suggestions and does not provide any detail regarding the process of implementation or operationalization.

Farooq and O'Brien Manufacturing Technology Selection Process

Farooq and O'Brien (2010) offered a process of manufacturing technology selection based on risk calculations and considering the supply chain opportunities and threats. The distinctive feature of this manufacturing technology selection framework was the assessment of risk of the manufacturing technology substitutes in the form of opportunities and threats in the supply chain and manufacturing environment. The framework was operationalized in a company case study. The authors highlighted that most of the previous studies were based on economic considerations, but were not capable of incorporating long term strategic challenges which are linked with the international competitive environment. They also observed the lack of empirical research which reflects the operationalization of the technology selection process. Based on the previous researches, they proposed a technology selection framework as shown in Figure 2.12. It involves six steps, where output of one step acts as input to the next step. The first step is regarding the evaluation of current supply chain, whereas the second step identifies the critical supply chain factors on which the company plans to compete. The third step proposes a long, medium or short time horizon. Step four is regarding the identification of the manufacturing technologies and generating a detailed characteristic list of each alternative. Step five recommends the assessment of identified technologies, whereas the last step advises the risk assessment of the selected alternative based on the risk adjusted technology strategic value and risk adjusted technology opportunity and threat value.

The research is reliant on the knowledge of the participant and technology managers are required to identify opportunities and threats linked with the selected alternatives. The authors mentioned research limitations and explained that lack of understanding regarding supply chain issues was the main reason behind their failure to identify and attribute values of each alternative. The case study was developed in an Aerospace Manufacturing Facility.

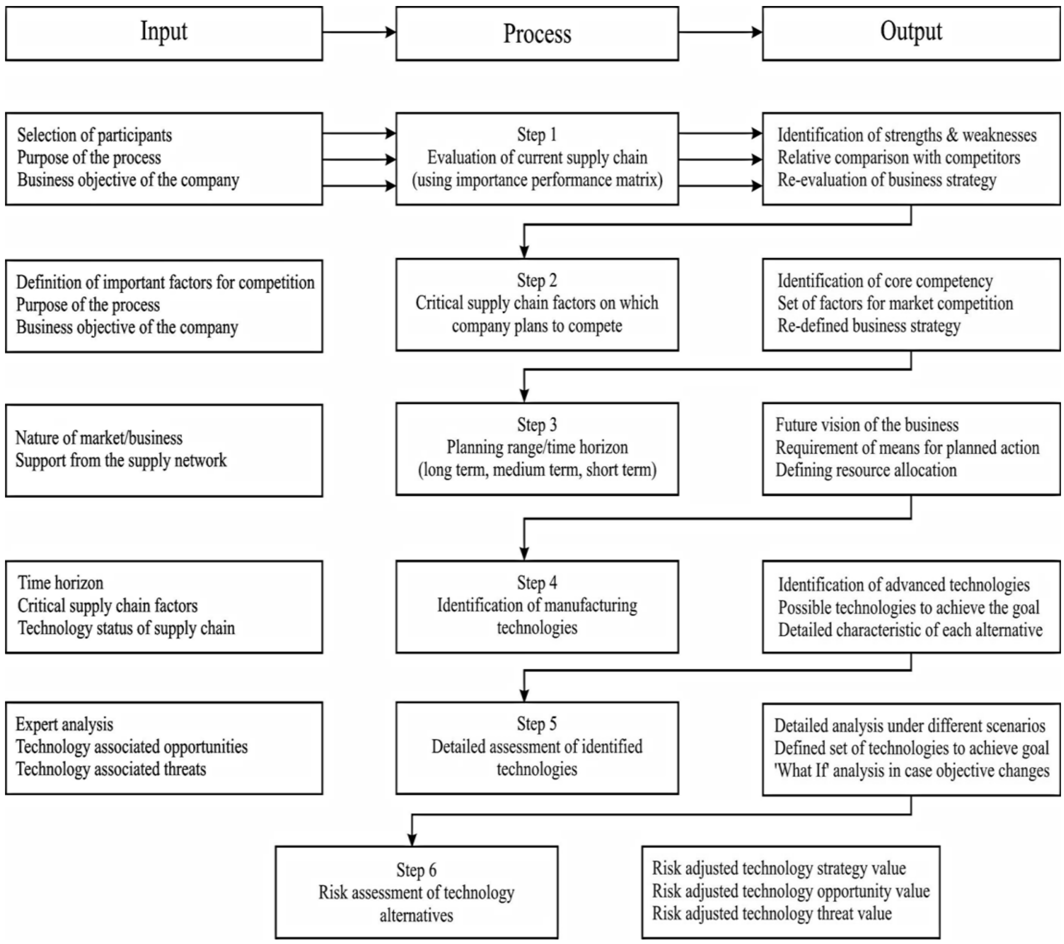


Figure 2.12: Farooq & O'Brien Manufacturing Technology Process (2010)

Difficulties like linking technology with business and selection of an emerging technology by a novice in an SME can be imagined from this case study. The research concludes that the solutions should be pre-emptive and practical with limited reliance on the users understanding and knowledge.

Chen, Ho and Kocaoglue Strategic Technology Planning Framework

Chen. et al. (2009) developed a strategic technology planning framework and presented a case of Taiwan's Semiconductor Foundry Industry. The development was established on the necessity of proper deployment of technology, to ensure a proper fit between technology and business. The study also highlights the synoptic planning mode which considers all business operations and strategic directions during the implementation process, while in adaptive planning, incremental plans are launched in reply to any change but integration factors were not stressed. The authors also highlighted the shortcomings of previous studies, which were limited to ideas or concepts only. The proposed framework is shown in Figure 2.13.

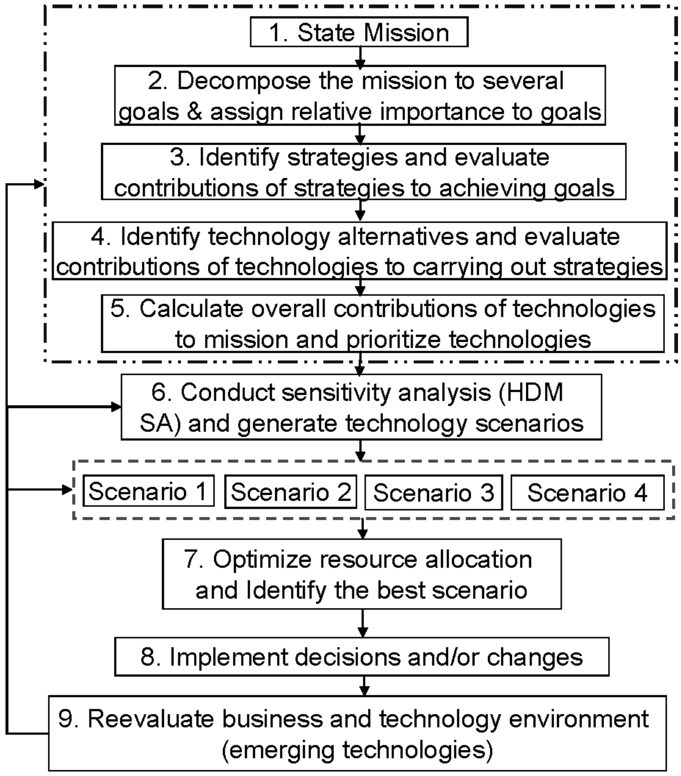


Figure2.13: Chen, Ho & Kocaoglu Technology Planning Framework (2009)

It starts from the establishment of the mission and is then further divided into several goals and ranked. The third step is regarding the identification of strategies and evaluation of their contributions to the strategies. The next step is the identification of technology alternatives to achieve the required goals. Step five and six analyse the overall contribution of technologies to the mission and perform sensitivity analysis. Subsequent steps suggest the different analysis scenarios for picking the best implementation option. Based on the above steps re-evaluation of the business is proposed in the final stage. The framework does not focus on the operational evaluation and does not provide any mechanism to link technology with business and current manufacturing operations.

2.10 Prior Studies regarding Rapid Prototyping Technology Selection

Due to the advances in the area of rapid prototyping, the numbers of available RP systems are growing rapidly, making the selection process more complicated. The available systems possess different capabilities on different criteria, and applications. Similarly, the technology adopters each have unique requirements, which must match with the capabilities of the potential technology alternative, to ensure the right selection of the RP equipment. Linking the technology with the company requirements is a complicated task and entails a complete understanding of all the technology alternatives. Grimm (2006) highlighted that,

"Selecting the right RP process can be difficult, but it is critical to the success. Picking a solution requires experience, information and understanding of a broad set of processes, techniques and technologies. This is a skill that few possess when expanding the scope to all additive (RP) and subtractive (CNC) methods".

The author also mentioned that most do not have the ability for right process selection. The study proposed a guide for selection but mentioned that this cannot be used as a selection tool for evaluation of the technology for purchase. Brown and Stier (2002) concluded that evaluating all the alternatives is challenging and task specific for those who have never encountered any RP system. Based on their experience they developed specific questions for the technology selection but mentioned that this is not a complete list of questions and is a starting point of thoughts for those who are part of the RP system selection process. Lennings (2000) reported that for the designer prototype development is based on either of two processes, Layered Manufacturing (RP) or Subtractive (CNC). The author developed some guidelines, but they are quite general in nature and any decision in a particular case will again be a daunting task in the absence of a well explained criteria and a decision support tool. Wall et al. (1992) raised some questions:

1. "For a given part, how can a choice among fabrication technologies be made?
2. Where should investment in new prototyping technology be focused?
3. How can new and existing prototyping technologies be evaluated?"

They developed a systematic method of evaluating prototyping processes in order to determine the best practice for a given situation. The authors collected data from a field survey at the Kodak Apparatus division and mentioned that the specific result from their study will soon be obsolete because of rapid advances in process development. The research was also not supported by any decision support tool.

Braglia and Petroni (1999) presented a management support technique. The paper described the issue related to the selection of the RP technology and attributed the low experience of the user with a variety of qualitative and quantitative criteria as the main hurdle to be overcome in the RP technology selection. The proposed ranked methodology included 20 commercially available systems and 5 main criteria and 12 sub-criteria. The user ranked the criteria and based on the results different RP equipment was evaluated. The comparison of the RP technology against the framework required expert intervention and was against the initial observation of the difficulties faced by low experience user in the selection of the technology.

Bibb et al. (1999) developed a computer based RP design advice system. The system was designed to assist the designer or project manager. Particularly those in small and medium sized companies, in planning the prototyping stage of product development. In this system, there are two types of rules: decision rules and calculation rules. The decision rule uses the input data to select the most suitable RP system. This data is derived from the STL file of the object. The system seems to be dependent on a limited number of systems available at that time. Moreover, the system takes a CAD model as input, meaning only technical input is considered whereas several criteria are not part of the final decision.

Masood and Soo (2002) developed a Decision Support System based RP system selection programme. The programme was a rule based Decision Support System which was the Visual Basic module of the M4 Decision Support System shell. The system incorporated 39 commercially available RP systems around the world and described that it was a most difficult thing to collect data from manufacturers if not impossible. The selector programme was based on IF-THEN rules. The first layer of the system was based on the country of the system developer, whereas the second layer consists of quick selection, detailed selection, build technology and machine style options. Every single option in the second layer was subdivided into several options like accuracy in XYZ axis, build envelope configuration, type of RP system laser or non-laser. The programme then raised a number of questions regarding the selection and based on this information suggests an appropriate system. The number of systems available has risen to more than 80, and as the world has become the global village where manufacturers have their resellers in all regions, such distribution will only result in limited choice and selection of equipment. The other issue is the absence of many critical selection criteria, which are an indispensable part of the selection. Selection criteria should contain both qualitative and quantitative factors like product profile, applications, surface finish and accuracy requirements etc. It should also have the ability to rank according to each user companies unique requirements. This provision is not available and is also mentioned by the authors in the limitation section of the paper. Grimm (2005) argued that there is still a parcity of techniques which can provide meticulous analysis, review and comparisons and further added that to achieve complete benefit of the RP technology, the properties of the technology should essentially coincide with the distinctive requirement of the company and even for an individual project.

Lokesh and Jain (2010) presented a systematic approach for RP selection based on the fact that selection is a tricky task due to the lack of industry experience. Methodology was illustrated by assuming fictitious decision makers. The authors developed an initial framework and then ranking was based on six key RP processes available worldwide despite the fact that tens of equipment fall under every single process, with absolute unique and independent process and technical parameters. The authors also mentioned that RP system selection requires a lot of information which can be obtained from journals, internet, manufacturers and by interaction with experts. This process itself is so complicated and is one of the great barriers in technology adoption. Grimm (2005) also pointed out that thousands of pages of information are available on the internet, but a detailed analysis technique is still required.

2.11 Limitations of the Preceding Technology Selection Research

Even though an integrated technology adoption approach, where the technology must be able to bind itself with the business strategy and operations, supplemented by an implementation mechanism is widely recognised and stressed in the published literature, it is still hard to find any designated research which fits all these criteria and requirements. Most of the research is inclined only towards limited factors, most critical of which was financial or cost justification.

The technology selection frameworks presented in this chapter do not clearly depict the relations between the technology, markets and business operations which must be triggered from the market and competitor requirements. Either one or a limited number of segments of the framework are elaborated which leaves no formal standard procedure for implementation. Product development should be the heart of any manufacturing technology selection effort due to its critical impact on the success of the business and is directly linked with the technology evaluation but such a vital link is missing even at conceptual framework development level making this framework inappropriate or less effective for any new RP technology adoption solutions.

2.12 Incongruity of the Technology Selection Studies for RP Adoption

Rapid prototyping is a revolution which has entirely changed the way business was done before and is still emerging. The RP technology offers a new set of strategies and solutions which are unique in nature. To exploit the great benefits offered by the technology, exclusive and dedicated solutions are required which are integrated and applied. Literature clearly shows that despite the great potential of RP, the technology could not penetrate the industry at large particularly in the SME sector. The summary of reasons for the low diffusion is:

i) Previous studies have not able to identify the distinct RP drivers due to the specific focus on the AMTs which does not include RP due to its emerging status.

ii) The absence of any integrated approach which can provide a complete guide from strategic to operational level.

iii) Selection of the right RP equipment is a great adoption barrier and no tool exists which is able to select the right RP technology based on specific requirements of the SME.

iv) Absence of complete and practical procedures with a complete effective tool kit to assist SMEs which are at the early stage of adoption.

Also, the previous developed frameworks are quite generic in nature, besides the limited knowledge of the decision makers about the new technology makes the framework unusable due to inability of the person to understand the intricacies of the interrelated (possibly conflicting) decision factors.

2.13 Concluding Remarks

The intense pressure on SMEs stresses the rapid advancement in both technical and managerial competencies to incorporate the advances, in order to minimize the gap between the external requirements and internal capabilities. In reality, the capabilities of SMEs to respond to such changes are plummeting leaving a wider gap, putting the Small and Medium businesses in a greater survival threat than ever.

The rapid prototyping technology is able to accommodate these companies to counter these challenges, but the internal structural issues of SMEs like low education levels and limited managerial and technical capabilities supplemented by the absence of any formal adoption mechanism are few of the causes of unusually low RP adoption in SMEs. The previous researches are mainly focussed on the adoption of AMTs and due to the higher investment costs are limited to cost benefit analysis. Most of the other frameworks are theoretical in nature and are based on an assumption that the users already have a complete understanding of the technology. RP technology adoption drivers are unique, and its adoption process should be able to address the issues which are linked with the SMEs and technology itself. The element of practicality is fundamental for success.

To overcome the inherent problems with the existing techniques, this research introduces the concept of the RPT adoption roadmap, which not only provides the answer of key questions, which are critical adoption barriers like why business should embrace this technology and what they need to do. It also provides comprehensive practical solutions from strategic external evaluation, to internal evaluations and selection of the right RP technology based on the user company requirement. The research not only provides new directions in the area of technology adoption by suggesting an integrated adoption framework but also provides practical solutions. It is anticipated that the research will help to reduce RP adoption barriers and will also have a positive effect on SMEs competitiveness and positioning in global value chain.

Note: Some of the sections in this chapter have already been published in following papers of the author

Ahmad A, Mazhar MI, Erik J (2009), 'Strengthening SMEs through Rapid Prototyping to meet future challenges Why & How? *14th Cambridge International Manufacturing Symposium* 24-25 Sep. Cambridge UK

Ahmad A, Mazhar MI, Howard IM (2012), 'A framework for the adoption of Rapid Prototyping for SME's: From Strategic to Operational International Journal of Industrial Engineering: Theory Applications and Practice, Vol.19 Issue 3, pp. 161-170.

3

RESEARCH METHODOLOGY

This chapter outlines the methodology used in the research and the process of developing a framework for the adoption of RP. The chapter begins with various research methods available and determines their suitability for the defined research objectives. The chapter further explains the research design process for the framework development and operationalisation process in detail. Reliability and validity of the research process is also the subject of discussion.

3.1 Research Paradigms

According to Keele (2011) two basic research methods are available named quantitative and qualitative, where quantitative research matches with the Positivist paradigm and qualitative research is close to the Naturalistic paradigm. Quantitative research is selected, stable, and quantifiable and is under controlled conditions whereas qualitative research is descriptive, dynamic and evolves theories (Grady, 1998).

3.1.1 Positivist Paradigm

Leong (2008) argued that positivism arose as a philosophical paradigm in the 19th century when Auguste Comte rejected metaphysics and declared that only scientific knowledge can surface the truth about reality. It was recognized as the dominant scientific technique by members of the Vienna Circle in the early part of the 20th century. Realist Ontology and Representational Epistemology are the beliefs of the positivist paradigms where the former assumes that there are real world objects from which humans are unaware whereas the later believe that people can understand this reality (Cohen & Crabtree, 2006). As per the positivist epistemology, science is taken as a way to reach truth, and to comprehend the world in a better way so it can be controlled and predicted (Krauss, 2005). Positivist research surrounds a single reality and can be performed independently. The defined research scope does not fit with the objectives of this paradigm as it involves multiple realities and demands strict interaction with the participants.

3.1.2 Naturalistic Paradigm

Storkerson (2010) argued that the naturalistic cognition is unremitting to practical judgements and assists in taking decisions and action by finding the current status, to accept it or change it. The following Para taken from Lipshitz and Strauss (1997, p. 151) classified the uncertainty barriers in decision making as:

- "Incomplete information is perhaps the most frequently cited source of uncertainty (Conrath, 1967).
- Decision makers are sometimes unable to act not because they lack information but because they are overwhelmed by the abundance of conflicting meanings.
- Finally incomplete information and inadequate knowledge."

In their next article Lipshitz and Strauss (1997) demonstrated that naturalistic decision making assists certain key areas of inquiry previously ignored. It helps in decision making by creating new models, procedures and for developing concepts. Keele (2011) compared the key assumptions of the Positivist and Naturalistic Paradigms as shown in Table 3.1. An important characteristic of Naturalistic research as mentioned above is the study of multiple realities in a holistic way with the critical participation of the researcher along with participants.

Table 3.1: Positivist & Naturalistic Paradigm Comparison of Major Assumption (Keele, 2011)

Positivist paradigm	Naturalistic paradigm
There is a single reality that can be measured.	There are multiple realities that can be studied only holistically and cannot be predicted or controlled although some level of understanding can be achieved.
The researcher and the research participant can remain independent of one another and not influence one another.	The researcher and the research participant cannot remain separate or independent. They interact and influence one another.
Findings of research can be generalized from the study sample to the larger target population.	Findings cannot be generalized beyond the study simple. Knowledge gleaned from the study in the form of “working hypotheses”.
Cause and effect relationships can be tested.	Cause and effect relationships cannot be tested since there are multiple realities that are continually changing so it is impossible to distinguish causes from effects.
Research can be conducted objectively and value free.	Research is subjective and value bound (i.e., the researcher’s own values).

3.2 Action Research Methodology

Action research is practical and solves real world problems. Reason and Bradbury (2006) exquisitely explained action research as:

“Action research is about working towards practical outcomes and also about creating new forms of understanding since the action without understanding is blind, just as theory without action is meaningless”.

Koshy (2005, p. 10) summarised that Action research:

1) Is emergent and participatory;
2) Can help to solve real problems;
3) Is about improvement;
4) Involves analysis, reflection and evaluation;
5) Facilitates change with inquiry.

Clarke (2005) argued that action research resembles the experimental research but applied in the real world by applying a small scale intervention in the real world operation where the impact of such intervention is closely monitored and ready for application. The Action research cycle defined by (Westbrook, 1995) is shown in Figure 3.1.

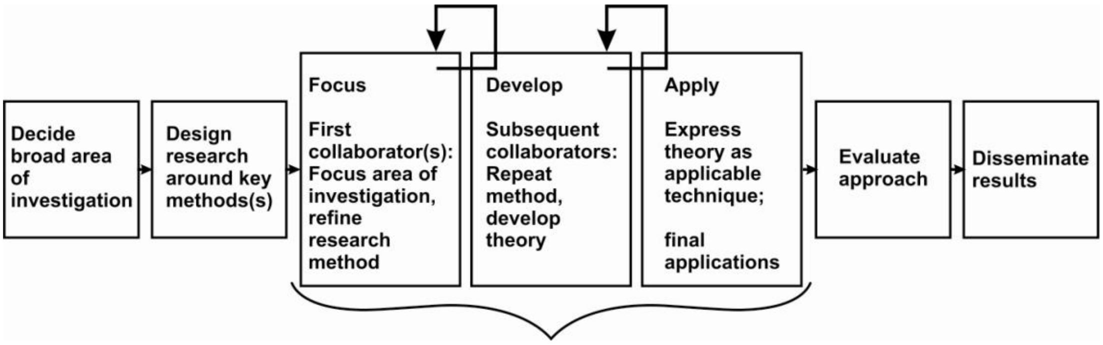


Figure 3.1: Action Research Cycle (Westbrook, 1995, p. 11)

This consists of the following four phases:

1) Planning: The first phase starts with the problem identification, collection of vital information, defining research methods and charting of an action plan.
2) Acting: Second phase deals with the collection of evidence, in other words implementation of the developed plan.
3) Observing: Third phase is regarding the analysis of the collected information, report writing and sharing of results with stakeholders.
4) Reflecting: The last phase involves evaluation and implementation of findings and often proposes that the process should be re-examined.

In short, action research in contrast to other research methodologies is practical and proposes solutions when a real world problem arises and requires close interaction of the researcher with the concerned stakeholders to devise practical solutions.

3.2.1 Action Research Selection Rationale

Positivist science has inherent weakness in knowledge creation and its ability to solve real issues. According to Susman and Evered (1978) many of the findings in research journals are tenuously related to the real world problems, which the organisations are facing. Voss (1988) also described that academic studies on the total process of implementation are limited. In reality, the practical world is quite different from the theoretical, and it is almost impossible to consider all the problems and assess the impact unless the researcher is deeply involved or becomes part of that system for close monitoring. One of the doctrines of action research is that any research conducted without the active involvement of the relevant stakeholder is unapt (Miller et al., 2003). Weaknesses in the area of Production and Operations Management (POM) research were indicated by Westbrook (1995) as;

1) Most of the POM research is based on modelling techniques. Even though the business and government can get multiple economic solutions from the models, the applicability of their results is always questioned by operations managers.
2) The most significant advancements in the last decade like JIT and TQM did not arrive from POM academics but from consultants and practitioners.
3) POM remained relatively weak in theoretical development.

The authors stressed the need for practical research leading towards practical solutions for managers, to be able to solve unstructured problems in the organisations.

One of the important rationales behind the action research deployment is a clear understanding of how the current system works and the development of courses of action for the sake of improvement and building of new theories.

An extensive review and investigation of the low adoption causes within SMEs determined that practicality is a real concern. The absence of any complete practical guide, which is able to satisfy their queries and concerns, is considered as a major cause of low adoption. The action research methodology makes it an ideal candidate for technology adoption related problems. Working closely with the relevant stakeholders, not only provided the direction for research but also helped to devise the solutions and theories which are applied, and viable and able to address the real world challenges.

3.2.2 Theory Generation through Action Research

Eden and Huxham (1996, p. 84) explained the contribution of AR in the theory building process as

- "AR generates emergent theory, in which theory develops from a synthesis of that which emerges from the data and that which emerges from use in practice of the body of theory which informed the intervention and research attention".

Action research is a strategy which helps to advance practice to bring the change and at the same time is able to develop and test a theory (Titchen & Binnie, 1994).

In an article, Whitehead (2009, p. 87) highlighted two types of living theories generated by Action research.

- The first is dialectical and grounded in living contradictions. The dialectical living theories generated through the action research process is “How I do what I am doing? In which I exist as a living contradiction.
- The second type of living theory is stranded in a relationally dynamic awareness which authors refers to inclusionality and explains as a “relationally dynamic awareness of space and boundaries as connective, reflexive and co-creative”.

Mcniff and Whitehead (2011) explained two main contributions of action research:

i) Contribute to the new practices;

ii) To contribute in the development of new theory and knowledge.

One of the well-developed theory development approaches in qualitative research is Grounded Theory, where action research is used to improve emergent theories, whereas grounded theory is used for retrospective analysis of the collected data (Sankaran & Tay, 2009). A combined cycle action research and grounded theory proposed by the authors is shown in Figure 3.2. As action research projects are situation specific and find solutions for a particular problem, one of the great action research challenges is the shift of theory of a core action project to a more generalized theory, so the wider community can take advantage. For example, an action research based project was initiated by the Royal College of Physicians and Surgeons and the lessons learnt from this research were reviewed in National Policy Development context (Meyer, 2000).

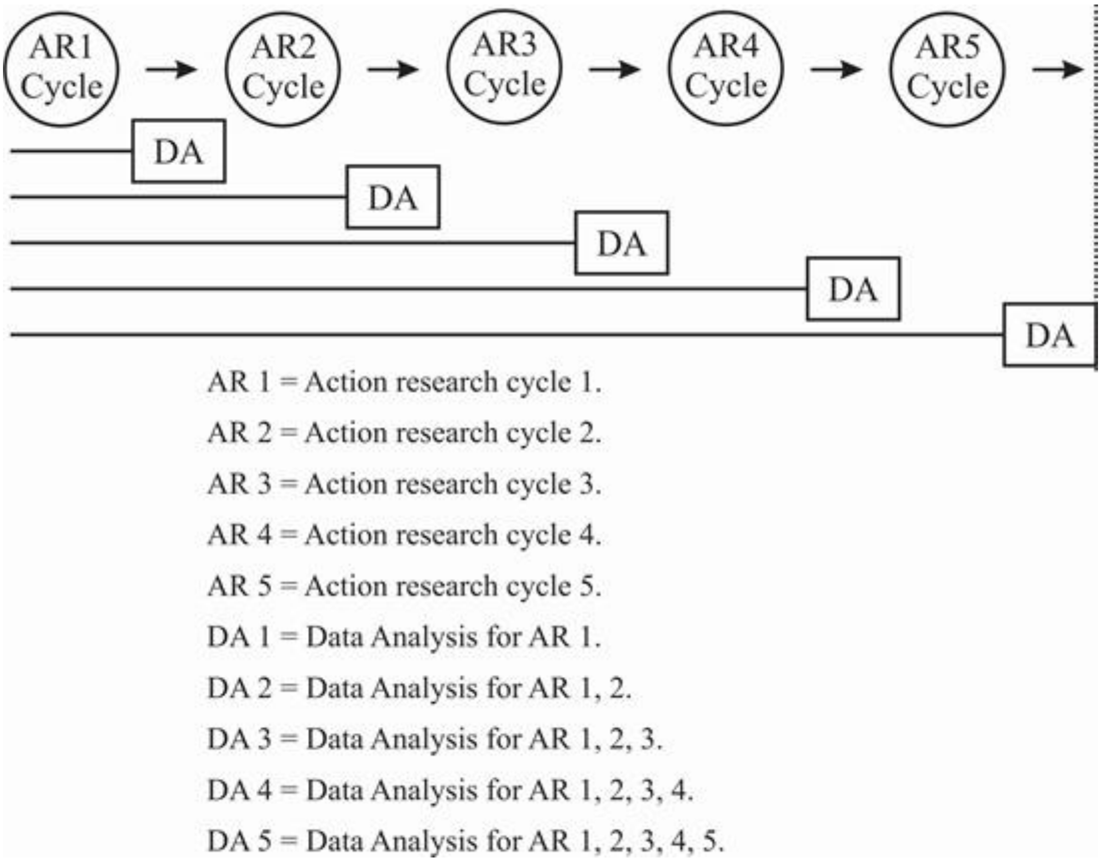


Figure 3.2: Action Research and Grounded Theory (Sankaran & Tay, 2009, p. 12)

Five principles were set by Thompson and Perry (2004) to generalise the quality of results of a core action project in other situations.

- Ontological appropriateness: How the prior theories and data triangulation from a number of sources are used to construct a more precise picture of a flawed world.
- Contingent Validity: The ability to demonstrate how the developed construct is able to operate in their unique setting.
- Epistemology: Capability to demonstrate the real world and also focus on value awareness of research.
- Credibility: Use of relevant quotes to maintain audibility.
- Analytic Generalisation: Identification of research issues before data collection phase.

3.3 Research Design

Research design sketches the structure of the research and considers how the different parts of the research correlates with each other in answering the research questions, and their contributions towards the achievement of the research aims and objectives. Research questions and methodology were carefully designed after field work, extensive literature review, experts and academic inputs, by considering the state of the industry and by considering the ineffectiveness of the previous research in the area of technology selection for RPT adoption. One of the important considerations of the developed work was its ability to generalize and its ability to respond to individual user requirements as user input always varies from one company to another. The implementation of the developed frameworks, tools and techniques will ultimately provide a comprehensive roadmap for the adoption of RP technology.

Stage I: The first stage as shown in Figure 3.3 explains the rationale of the research and identifies the problem areas and finally proposes a RP adoption framework.

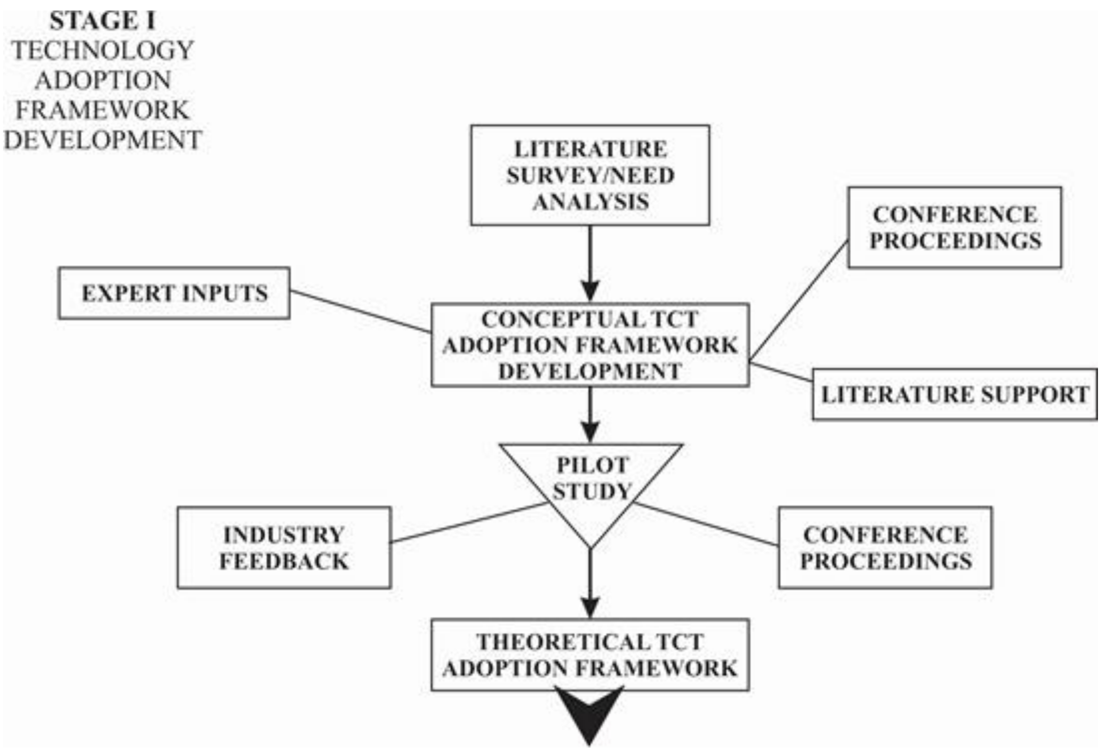


Figure 3.3: Research Design Phase I

Stage II: The second stage comprises of the operationalisation of the developed framework through industrial case studies through Action Research in a developing and developed country.

STAGE II

FRAMEWORK OPERATIONALISATION

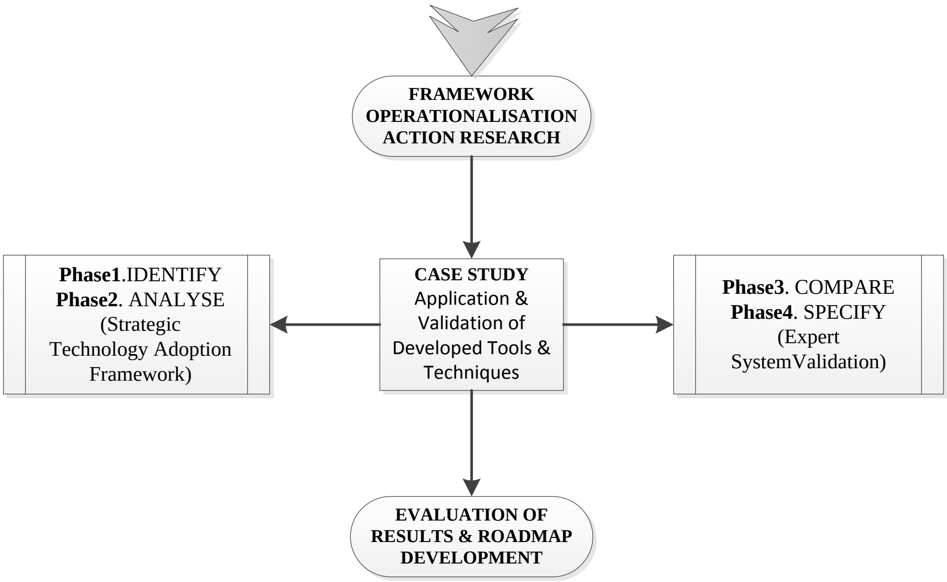


Figure 3.4: Research Design Phase II

3.4 Stage I/RPT Adoption Framework Development

The first part of the research was the development of the technology adoption framework to be able to accelerate the RP adoption effectively. The vital considerations of this development were:

1) It should be comprehensive, able to address the current challenges, facilitate links of technology with the internal and external environment and provide competitive advantage.
2) Operationalisation capability of all steps mentioned in the framework and development of methodology, tools and techniques to facilitate the practical applications.

The development of the framework was instigated from comprehensive industrial input and literature review and analysis and involved several steps which are explained in detail in the next section.

3.4.1 Need Analysis/Literature Survey

Needs analysis was utilised to obtain a clear understanding of the SMEs problem with RP technology adoption and to address the issue and explore the reasons for the low adoption. A detailed review of the literature was conducted to establish the research base. Organisation's looking after the SMEs issues were consulted. Expert reports on the low adoption challenge were examined for the deep understanding of the issue. By considering the literature and business issues, the research goals and direction was made clear with an aim not only to provide a significant contribution in the area of technology adoption but also to provide practical solutions which can be beneficial for SMEs.

3.4.2 Conceptual RPT Adoption Framework Development

Once a deeper insight into the issues was developed, the next pivotal step was to connect these pieces together to get the solutions applicable for these complex situations. A detailed review of the previous work in the area of technology selection assisted to develop an initial technology adoption framework in the form of interlinked processes, to meet requirements from strategic to operational level. The developed framework must be capable to meet specific RP adoption requirements by considering the problems SMEs are facing and at the same time should have the ability to generalize to other technology related problems.

3.4.3 Pilot Study/RPT Framework Development

Jabareen (2009) argued that selected contents of the framework should be able to effectively epitomize the related cultural, political and social behaviours phenomenon and suggested that these should come from a variety of sources like books, articles, newspapers, essays, interviews and practice. A similar approach was adopted for the development of the RPT Framework. The capabilities of SMEs and their challenges were observed initially for a period of around two years. The technology was than studied in detail and links were established between technology and the SME's challenges.

Validation of the theoretical framework's contents is a significant step at this stage, to ensure that they are reasonably agreed by experts working in the area. Jabareen (2009) explained the validation process as "Validating the theoretical framework is a process that starts with the researcher, who then seeks validation among outsiders. Presenting at a conference or some other type of academic framework provides an excellent opportunity for the researcher to discuss and get feedback".

Initial validation was carried out by sharing the developed framework with academics and industry people to receive feedback and for the sake of refinement.

The refined version was presented at several International Conferences and in the form of a journal paper. One of the utmost benefits and advantages of presenting these concepts for discussion was that experts from different countries with all different backgrounds shared the issues they observed and provided their valuable inputs. With the guidance of these experts, the research was able to turn the issues observed in one country into a much broader and generalized form with no boundaries. The four stage framework is explained in detail in Chapter 4.

The developed framework considers the model proposed by Farooq (2007). It has the ability to cover all aspects that need to be considered in the implementation process as urged by Voss (1988). These include pre-installation planning and justification as well as purchasing, commissioning and evaluating the technology under consideration.

The guidelines given in German Standard VDI2206 for system design, proposed by the Association of German Engineers, were also considered for ensuring that the developed framework was practical and useful to resolve the technology related issues. The VDI-2206 module is shown in Figure 3.5

3.5 Stage II/Operationalization Process Development

Stage two of the research concerned the operationalization of the developed systems using real case scenarios for the sake of the practical roadmap development. Two companies one in Australia (Developed) and other from South Asia (Developing) were selected for operationalization. The purpose of this selection was to develop a deeper insight into the issues they have, and challenges they are facing to get the roadmap relevant and practical for both developed & developing nations. Value stream analysis was conducted in the South Asian company on a mega nationwide project which lasted several years and was recently completed. The main motive behind this selection was:

a) To evaluate the existing procedures of product development and to find the link of RPT with the issues they are confronting.

b) To determine the role of RPT in product development cycle and its impact.

c) For a greater access on the information which is otherwise difficult to discern in a developed country due to extremely strict regulations.

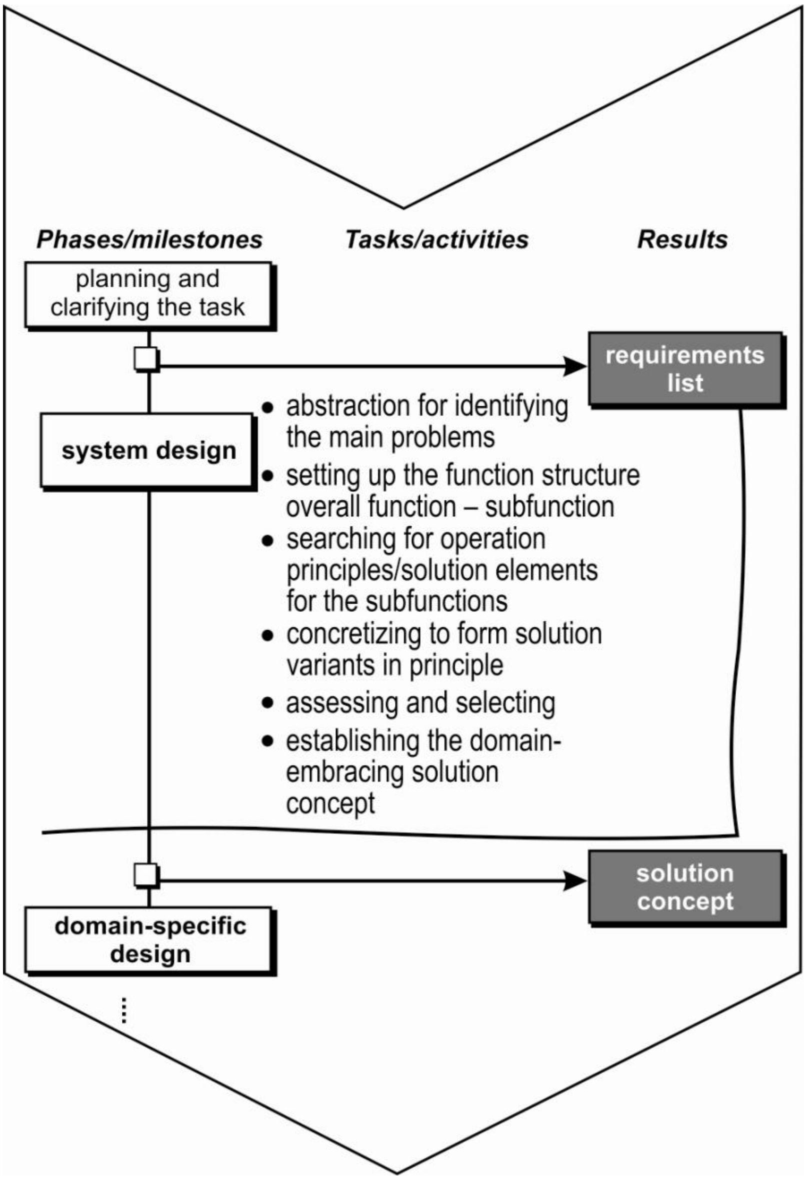


Figure 3.5: VDI-2206 Open Process Module (Bathlet)

The operationalization process comprises the following four stages:

3.5.1 Identify

The framework begins by first evaluating the market and competitors. This provides an excellent starting point, by giving an overview of the current strengths and weaknesses of the business, their real challenges and requirements of the current and future markets.

Competitor comparison is a critical activity which helps to benchmark where the company stands compared to the competitors and to set goals for the future by overcoming the current identified gaps (Wheelwright & Clark, 1992). Products like air cooled cylinder engines, fluid tanks and telecom shelters were selected from both companies. Data were collected through designed questionnaires and semi structured interviews. Decision Support Systems based on AHP methodology, were developed to quantify the current positioning of the companies to get a full picture of current market demands and positioning of the companies.

3.5.2 Analyse

Once the competitor and market position were determined, the gathered information serves as input to the second phase which deals with the evaluation of internal capabilities, requirements, strategic position and current Technology-Strategy link, current performance appraisal by considering operational, cost, marketing and technology parameters.

The process was conducted by the completion of an important performance questionnaire by the senior managers of both companies having decades of experience. The criteria developed in the questionnaire were also the subject of discussion to make it more relevant by eliminating or merging the factors. An exclusive micro analysis of the product development value chain was also conducted by using a novel method to critically evaluate the current procedures and to determine where and how RP can make a significant change. A framework which not only depicts the relationship between technology and strategy but was also able to identify the gaps was also developed during this process.

3.5.3 Compare

An abundance of technological alternatives with different cost, technical and application parameters have made the selection of the right choice of technology a very complex task. Limited knowledge of the user company makes this task much more difficult especially when the technology is emerging.

The RP technology selection parameters were identified with the help of an extensive literature review and after consultation with experts in the area. The identified parameters were transformed into a framework, which includes all technology, operational and cost drivers which must be considered into any technology related decision. The framework served as an input to the development of a Decision Support System called Expert Choice which works on the principles of Analytic Hierarchy Process (AHP). The input was taken from managers and based on their unique requirements as the RP equipment was selected. The Decision Support System is able to provide a means for integrating economic and non-economic, qualitative and quantitative factors.

3.5.4 Specify

Once technology has been identified in the previous step, the evaluation of the selected technology and its relationship with the manufacturing strategy will be established. It includes the opportunities it offers, adjustment of the business strategy, impact assessment of technology on the business and human resource requirement. These were suggested as critical requirements to consider before any formal technology deployment decision is taken. The framework suggests that this cycle continues with the regular expert review and for exploitation of benefits after the deployment of the technology. This can create a new world of opportunities which cannot be realized during the initial phase.

3.6 Data Validity & Reliability

The procedures used for validity and reliability of experimental research are not valid in the case of action research. Action research does not have to justify itself in relation to alternative epistemologies and research approaches (Susman & Evered, 1978). Altrichter et al. (1993) argued that quality criteria and procedure developed for experimental setup are difficult to implement in action research even though they are also essential. Jean and Jack (2002) claimed that validity is not regarding the selected methods, but the authors proposed two criteria for action research approach judgment. The first is the comparison of action research reports in the context of traditional research, and the second concerns what kind of criteria shall be used to evaluate them. Holter and Schwartzbarcott (1993) reported that action research is the most enthralling methodology to bridge the gap between theory, practice and research. They further mentioned that no specific data collection techniques are required, and the methods like observations, questionnaires, interviews and action experiments are typically the data collection method. Heikkinen et al. (2007) underlined the following five quality criteria for action research:

- “Analysis of History of Action: How the action evolved historically and how logically it proceeds?

- Principle of Reflexivity: Researcher’s relationship with his idea of research and how transparently the researchers explain his materials and methods.
- Principle of dialectics: How the researcher’s insight developed in consultation with others, interpretations and authenticity.
- Principle of workability: How clearly the research is applicable in practice? How are the ethical issues handled? How the research encourages new practices and actions.
- Principle of Evocativeness: How well the research narrative conjures mental images.”

The data triangulation is the other method used for the validity of the proposed research, which involves the use of qualitative and quantitative methods, multiple and different resources to highlight the research issues and its outcomes (Farooq, 2007; Stringer & Genat, 2004). Several data triangulation techniques were proposed by Shih (1998), which are:

Investigator triangulation: is a research team or thesis committee with a shared interest of the topic.

Data triangulation: Multiple sources of data, collection of the data for the same phenomenon.

Theory triangulation: Use of existing theories during the research process and the theoretical diverse background of the researcher.

Method triangulation: includes the use of more than one method or data collection techniques. This includes observations, structured interviews, questionnaires etc. and the use of both qualitative and quantitative techniques in the same study.

Both the quality principles and triangulation techniques were strongly adhered to during the entire research process. This included the historic evolution of study, close interaction of the researcher with the selected companies, their issues and the RP technology, the critical issues of low technology adoption and its relationship with the SMEs challenges.

The data triangulation was achieved by using multiple data sources and in two different geographical locations. These include questionnaires, structured and semi structured interviews, working closely with industry and observations. Both qualitative and quantitative techniques were deployed like Strategic technology adoption framework, important performance (IP) analysis and Analytical Hierarchy Process (AHP) which employs both qualitative and quantitative inputs to achieve the desired outcome.

3.7 Research Implementation in Real Environment

Since one of the greatest barriers identified during the research process was the lack of practical solutions which can guide the complete adoption process, the other purpose was also to examine the current practices and to observe the capabilities of the technology to meet their issues and challenges. The exposition was necessary for a large proportion of SMEs, who still believe that technology is irrelevant for them. Two medium sized companies one from Australia and the other from South Asia were selected for the sake of practical RPT adoption roadmap development, through the application of developed frameworks, tools and techniques.

Action research requires an active involvement in the company business operations and a huge amount of information from the management. This requires an extensive time and resources as compare to other mode of research. Dick (1994) explains the requirement of number of action research case studies as

"*One of the way in which you can secure more generalisability, if that is important to you, is by doing multiple studies. So instead of doing one case study for instance you could do two. If you have chosen them to be pretty diverse, then those things that you find in both of them, it seems to me can with some caution be generalizable".*

3.7.1 Company A

Company A belongs to a country in the South Asia area. The company is medium sized and has been in business for over thirty years and is the pioneer of fibreglass products in the country. Today company A is one of the largest telecom infrastructure providers in the country and has decades of manufacturing experience in products like altitude shelters, alarm systems, precision fit luggage, electric distribution boards, steel towers, monopoles, chemical plant equipment, tube well pipes, cold chain products and aerospace equipment etc.

The Senior Management of the company including the General Manager and the Production Manager were the contact persons and with their guidance and instructions other Design and Operational Engineers were consulted when required. The period of the case study was from November 2012 to February 2013, during which time two to three hours were spent daily with the relevant personnel, depending on their availability. In the analysis, company A is mentioned as Alpha or Company A for the sake of differentiation from competitors.

3.7.2 Company B

Company B was selected from Australia. The company is a leader in specialized engine and vehicle systems. It provides engine and vehicle technologies and alternative fuel solutions. The primary business activity of the company is Auto gas and Sprint systems and it is also actively involved in the consulting services.

Developed frameworks were refined with the consultation of design engineers of the company. Input for the evaluation of competitors and markets were also taken from the company. Decision Support System validation by taking the real products developed by company also formed part of the research process. The practical work started in May 2011 and lasted until September 2012. In the analysis it is referred to as Bravo or Company B.

3.8 Concluding Remarks

This chapter has laid a foundation for the methodological procedures for the proposed research. The research process and its components have been identified. The companies have been selected for data collection and validation. The research process has also been elucidated, and every single step of the research has been explained. Reliability and validity issues were also described, and how they were maintained was also the subject of discussion. An overview of the tools and techniques were also given in the chapter.

The next chapter will explain in detail the RPT adoption framework phases and the complete description of all the techniques and tools employed during the course of the entire research.

Note: Some of the sections in this chapter have already been published in following paper of the author

Ahmad A, Mazhar MI, Howard IM (2012), ‘A framework for the adoption of Rapid Prototyping for SME’s: From Strategic to Operational International Journal of Industrial Engineering: Theory Applications and Practice, Vol.19 Issue 3, pp. 161-170.

4

DEVELOPMENT OF TOOLS AND TECHNIQUES FOR THE RPT ADOPTION FRAMEWORK

Based on the research methods outlined in the previous chapter, the RP technology adoption framework will be developed in this chapter. The chapter explains all critical steps mentioned in the framework. The tools and techniques deployed to develop a practical roadmap are also the subject of discussion.

4.1 RPT Adoption Framework

In view of the limited applicability of the previous technology related work for RPT adoption, by taking the experts' advice and by observing the challenges and practical difficulties of RPT adoption, a comprehensive and integrated RPT adoption framework is proposed.

Manufacturing strategy is one critical area which helps to determine the competitive position of the company in the market place and is directly linked not only with the external environment which includes the market, customer and competitors but is also closely linked with internal business functions like technological capabilities and human resources. According to Cil and Erven (1998) it is the most neglected area and of increasing concern. It is related to management principles regarding how the product is manufactured, deployment of resources and organization of the required infrastructure. Platts and Gregory (1990) argued that the strategy can be formulated, or it emerges from a changing scenario. They also stressed that because the strategy is concerned more with the unknowns than uncertainties, the events cannot be predicted in a probabilistic way and therefore the decision process should be delayed as soon as the most relevant information emerges. This is exactly the case of RP adoption where more unknowns exist, so it is almost impossible to predict manufacturing strategies specifically for an SME. Grieves (2006) in the CIM data white paper explained that even though RPT is able to overcome many issues which negatively affect manufacturing effectiveness, it is still essential to make the process in line with the capabilities of RPT to achieve the maximum benefits. The author claimed that a majority of implementations consist of point solutions which only consider a small proportion of the RPT advantages and emphasis on the integrated solution.

An integrated framework capable of facilitating RP adoption from strategic to operational level is shown in Figure 4.1. The framework explains the required input, describes the analysis process and then mentions the output of that process. The framework consists of four major steps which are the discussion topics of the next section.

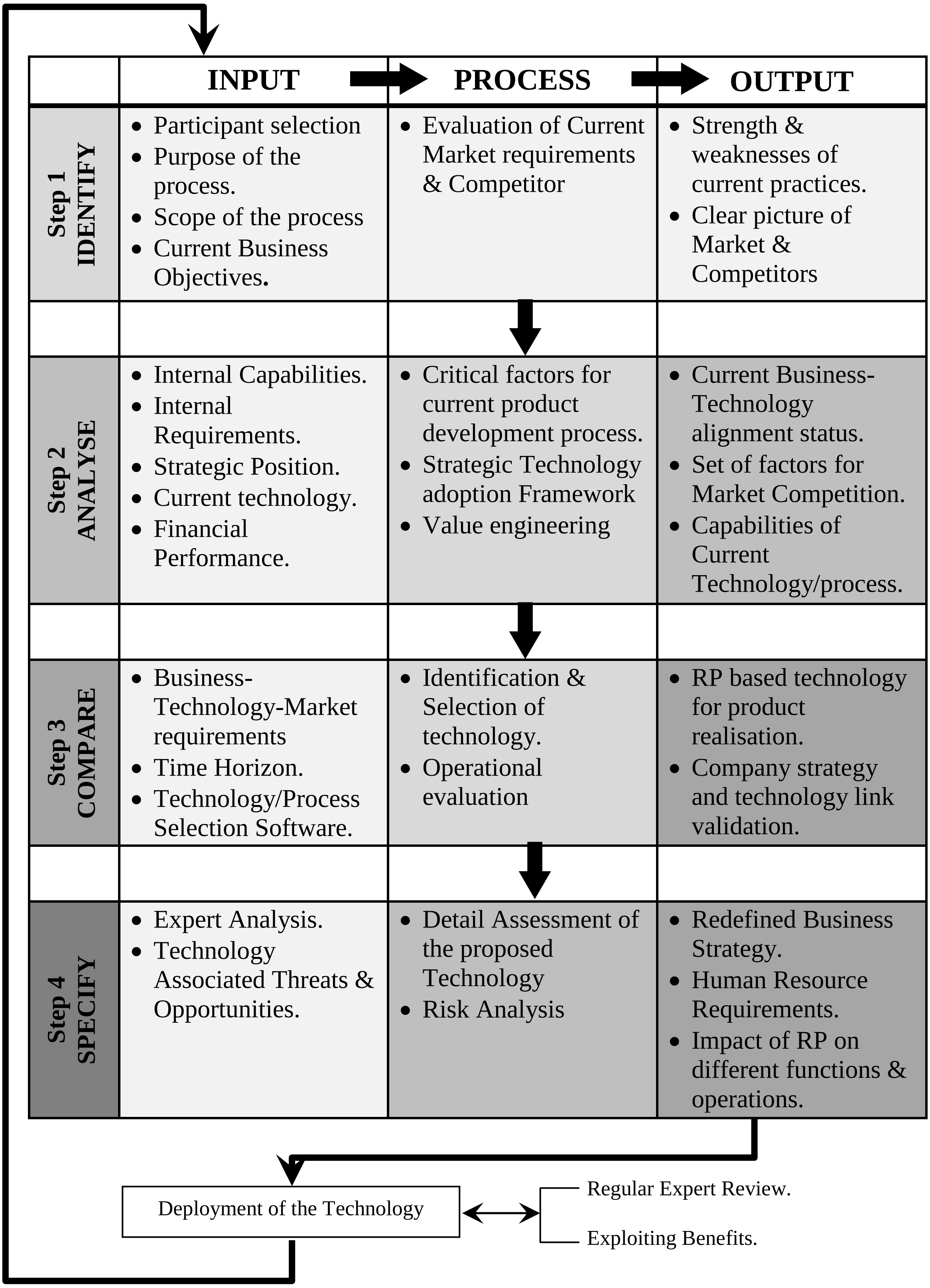


Figure 4.1: Proposed RP Based Technology Adoption Framework (Ahmad et. al, 2012)

The developed framework is able to direct the development of successful corporate, business and manufacturing strategies.

4.2 Framework Operationalisation Process

A simplified model shown in Figure 4.2 represents four interlinked processes for the operationalisation process.

- IDENTIFY/External Environment Analysis: Evaluation of the Markets and Competitors.
- ANALYSE/Internal Business Analysis: Analysis of current product development process, current technology strategy link and value engineering.
- COMPARE/Technology Selection: Selection of the RP equipment and operational evaluation.
- SPECIFY/Impact Assessment: Assessment of the impact on the product life cycle and assessment of risk.

4.2.1 IDENTIFY/External Environment Analysis:

The first step of the framework is the assessment of the external environment which includes the market and competitor analysis. This is a very crucial step which requires the involvement of all stake holders including the senior administration,

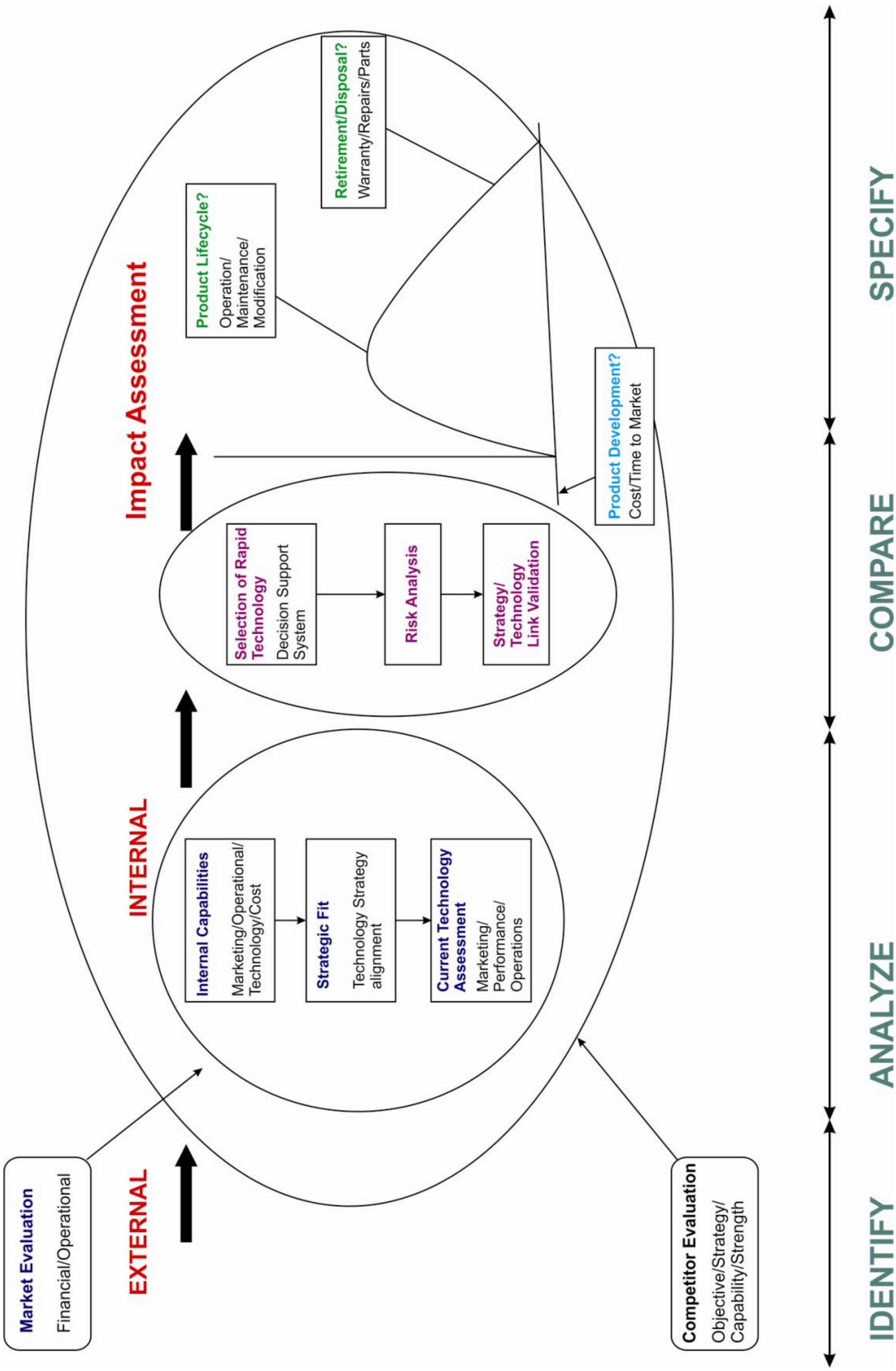


Figure 4.2: Schematic of RP Adoption Model

having an excellent understanding of the customer demands, market drivers and who know their competitors very well. It also provides an excellent starting point in understanding the market dynamics and where the company stands against its competitors. It is anticipated that it will help the company to review and readjust their current strategy. Any move towards the technology advancement can be ineffective unless the company truly understands the external environment and any current or future challenges they are facing.

Slack (1994) described this process as “Ignorant of their own ignorance” during their practical case study process and shared the typical reaction of the managers “I did not know how little we knew about our customers and especially our competitors. Despite the critical importance of the true understanding of the external environment analysis, no formal procedures exist at SMEs for the evaluation process. Cil and Erven (1998) concluded that the competitive position of a company is entirely dependent on the relation between manufacturing ability and market demands.

One of the most significant activities at this stage is to determine the criteria for competitors. Several factors have been considered not only from previous literature but also from discussions with participants. Alessandra et al. (1990) recommended specific criteria which includes market share, financial picture, quality of the product, experience within the advertising industry etc. The critical success factors which have capabilities to influence the competitive position have been defined under the categories of economic, technical and operational parameters. Leidecker and Bruno (1984) indicated economic and technical variables only, but discussions with senior managers revealed that operational parameters which are concerned about the products quality, market share and its acceptance are also essential for a better position of a company in the market. Around fourteen criterions were identified for the development of the Competitive Profile Matrix (CPM) as shown in Appendix A. Based on the ratings obtained through CPM, an Analytical Hierarchy model is developed, which clearly identifies the position of the company against its competitors.

Ahmad et al. (2012) argued that the global economic scenarios have posed significant threats to companies around the world, where the increased variety and short lead time are some of the future challenges that SMEs are facing. Pretorius and

Wet (2000) identified the low product price, short lead time and variety as the attributes of the current world markets and stressed the need for low manufacturing cost, short process lead time and process flexibility to meet these challenges. The next important step after the competitor analysis is the evaluation of the markets through a questionnaire (Appendix B). The purpose is to identify the nature of the current market drivers and to get a clear picture of the changing dynamics of market forces. The measure is indispensable especially for SMEs to understand the changing mechanisms and to develop new strategies to align the business operations with market requirements. The focus of this step is the clear understanding of the nature of markets, product related requirements and market demands. This step also collects vital information regarding the role of technology and gets an in depth knowledge of company procedures related to technology, business and operational performance evaluation.

The output of this first step is to get a clear picture of the market and competitors, which is an excellent starting point and is useful in operational evaluation and its alignment with the business and market strategy.

4.2.2 ANALYSE/Internal Business Analysis

The second step of the framework operationalisation concerns the evaluation of internal business operations to determine its ability to deliver and to highlight the potential gaps or mismatches between the external demands and current capabilities. This stage also determines the role that RP technology can play to minimize these gaps.

The Importance Performance (IP) analysis, development of the Strategic Technology Adoption framework (STAF) and Value Stream Analysis (VSA) are the key processes involved in this step. The description of each technique is described in the coming sections.

4.2.2.1 Importance Performance Analysis:

Determination of the factors responsible for upholding the competitive advantage and meeting customer demand is the first crucial step towards the development of an operational strategy, which is also in line with the business strategy. The next vital step is to prioritise these factors to ensure that every factor receives the necessary attention and resources. This step confirms that all the efforts made are in the right direction with a minimum probability of waste. Martilla and James (1977) expressed the difficulties in translating research results into action and explained that the research may have studied only one side of the customer acceptance that can be either importance or performance attributes rather than both. The authors developed an importance-performance grid where the ratings were obtained on a four point scale. Based on their practical work, Slack (1994) proposed a nine point scale which departs from the original four point scale proposed by Martilla and James (1977). Operational performance was evaluated based on the nine point criteria developed by Slack (1994) and is shown in Appendix C. Around thirty three criterions on which RP is able to influence have been identified (Appendix D). The inputs from the practioners are plotted on an Important Performance matrix.

4.2.2.2 Strategic Technology Adoption Framework

Linking the business with the technology is the recipe of success, and this is only possible when decision makers are fully aware of the competitive benefits offered by different technologies (Ahmad et al., 2009). The strategic planning phase is the combination of business and technology by taking a long term strategic view of these functions (Cil & Erven, 1998). The developed framework is an attempt to link the business direction of the company with the characteristic of the available prototyping technologies which includes both additive and subtractive technologies. Each technology mentioned in the framework offers unique characteristics which are suitable for a particular customer and market requirements.

The company can locate their business on the strategic grid, with the option of selecting one or more technologies according to their customer needs and the market in which they operate. The developed framework shown in Figure 4.3 considers, Sharif (1994) the framework of integrating strategic mixes to the markets as reference.

The integration process is structured by considering the technology characteristics and dynamics of the changing market, as the current trends are low volume and high customization at a reasonable price & quality. The manufacturing sector needs to anticipate what is coming in the near future and this is only possible when they have a clear understanding about the latest technology and strategic advantage it offers.

			MARKET STRATEGY			
			High Standardization	Medium Standardization	Differentiation	Personalization
			Limited response	Moderate response	High response	Quick response
			Limited Customization & Complexity	Moderate Customization & Complexity	High Degree of Customization & Complexity	Individual Requirements
			Low Flexibility	Moderate Flexibility	High Flexibility	Quick Production
			Time To Market High	Time To Market Moderate	Time To Market Low	Time To Market Very Low
TECHNOLOGY STRATEGY	Emerging Technology	Planning for Emerging Product Development (**RM**)				Novel Markets
	New Technology	Adoption of the latest product development**(RP)**			Turbulent Markets	
	Moderate Technology	Adoption of Standard Technology(**CNC**)		Stable Markets		
	Traditional Technology	Use of Traditional Product Development Technology(wooden pattern etc)	Highly Stable Markets			

Figure 4.3: Strategic Technology Adoption Framework (STAF) (Ahmad. et al., 2009)

The growth of the firm and the technology it adopts are interlinked and constitute a substantial factor in determining the cost and quality of the products it produces (Sharif, 1994). The proposed prototyping technologies also have a dramatic effect on the lifecycle of the product. Highly stable markets rely on traditional product development procedures for high standardized markets. Stable markets can serve medium standardization, whereas turbulent and novel markets require new and emerging technologies.

4.2.2.3 Product Development Value Stream Analysis (VSA)

The purpose of performing VSA in the context of RP adoption is to understand why one needs to consider the RP adoption and how much the technology is able to influence the product development process. This step is also important to see the impact of the technology on any product development related activities. There are a number of reasons to perform the VSA which are:

- To determine the capacity of current procedures to deliver the required output/outcomes.
- To indicate the area where interventions or modifications are required.
- Determining the role of RP technology in overcoming the identified issues and challenges.
- To assess the impact of RP on the life cycle of the product development process.

Product development is one of the weak areas especially in SMEs. Despite its vital role in determining the position of the company, not much attention is paid to this. Cooper and Kleinschmidt (1986) in their survey of 203 companies concluded “What the literature prescribes and what most firms do are miles apart when it comes to the new product-process”. They also revealed that market study, trial sell and detailed business analysis are done in only 22.5% cases, whereas customer reactions to the proposed new product were markedly absent. Huang et al (2002) revealed that there is diminutive empirical research into the effect of the strategy and skills on excellence and comprehensiveness of the new product development programmes particularly in SMEs, despite the fact that they need to develop and innovate more proficiently. Parasad (1998) highlighted that the conventional techniques of handling with “short term fixes” in “reactionary mode” for product development have not been enough to justify snowballing global competitive pressure. According to Wheelwright and Clark (1992, p. 29) “Even in many successful companies, new product development is seldom fully realized, the process is tinged with significant disappointment & disillusionment, often falling short of both its full potential in general”.

Haque and Moore (2004) pointed out that inadequate published literature exists on the performance measurement and metrics for new product introduction over the last ten years. One evolving research direction is the impact assessment of organizational variables on the firm’s ability to reduce the new product development time and cost (Afonso et al., 2008). Poolton and Barclay (1998) conclude that “if companies can improve their effectiveness at launching a new product, they can double their bottom line; it is one of the areas left with the greatest potential".

Value Stream mapping is based on the lean principle. McManus and Millard (2002) described the product development VSA as one way for a quick response to customer needs for new products or variations in the previous ones. Since the theoretical development, even though some case studies have been published there is still a dire need to understand how the tool can be used in practice and how the theory is able to assist (Lasa et al., 2008).

By bearing in mind the product development challenges at SMEs and to determine the role of RP, a distinctive approach "micro value stream analysis" has been adopted to explore the entire product development process at the micro level.

Software called Proplanner which is basically designed for material flow analysis on the shop floor was modified to apply to the product development process. This modification in the application is based on the fact that information flow is used instead of original material flow. A special permission for using the software licence (at no cost) was granted by the President of the Proplanner, after discussion concerning the objective of the software use with proplanner experts.

Two commercial modules of the proplanner named "Protime Estimation" and "Flow Planner" (working in AutoCAD environment) were used to explore the product development process in a novel way.

Protime Estimation module organizes the task time data in an easy to use spread sheet format. Data from a real product development project was collected and analysed to break the time into observed, estimated or calculated time. This allowed for easy input independent of what types of time information is already documented.

Flow Planner module generates the material flow diagram and calculates the material handling travel distances, time and cost. With variable line-width line colours-coded by part, product or material handling method it is easy to observe the excessive material handling*. The similar principle was applied during a real product development process to discern how the information and material flowed during the process.

* Taken from http://www.proplanner.com/en/products/flow_planner/

4.2.3 COMPARE/Identification and Selection of Technology

The third critical phase was the selection of the prototyping technology suitable for the product development process. Lack of knowledge about the new RP technology, abundance of available RP systems and selection of the prototyping technology based on the individual user company requirements are few of the barriers in the adoption of new RP technology. To address these challenges effectively, a two-step approach was used:

- To develop a comprehensive selection criteria with a specific focus on SME issues.
- Development of an Analytic Hierarchy Process (AHP) based Decision Support System to assist in the selection of the right process/technology.

4.2.3.1 RP Based Technology Selection Framework Development

Technology identification and selection processes are required to concentrate on the available technology attributes and the individual user/company requirement. There are more than 80 commercially available RP systems all with different capabilities. A right selection of the equipment requires an exceptionally strong iteration between the technical and cost parameters and existence of such information at SME level is scarce. Large numbers of SMEs particularly in developing countries still rely on traditional prototyping processes like CNC which is subtractive in nature. Despite its limitations this process can be used in many applications where it has advantages over the RP (additive) process. In some scenarios, the decision has to be made as to whether a company should buy RP equipment or should utilize the facilities offered by a service bureau. The real challenge is to choose the right technique first (additive, subtractive or service bureau) and then select the most suitable equipment/ technology amongst a long list of commercially available RP systems.

After an extensive search of RP literature, the selection issues and by considering the SME state and challenges, around fifty four criterion were identified which should be considered during a selection process. The identified criteria are grouped into four main criteria, eleven sub-criteria and thirty nine lower level criteria as shown in Figure 4.4.

The main criteria are considered the most important factors which includes the selection of materials used for the prototyping/manufacturing process, the required profile of the product, and the potential of the selected technology to produce the desired surface finish and accuracy and process economy which considers all cost related factors. The complete framework is shown in Figure 4.4.

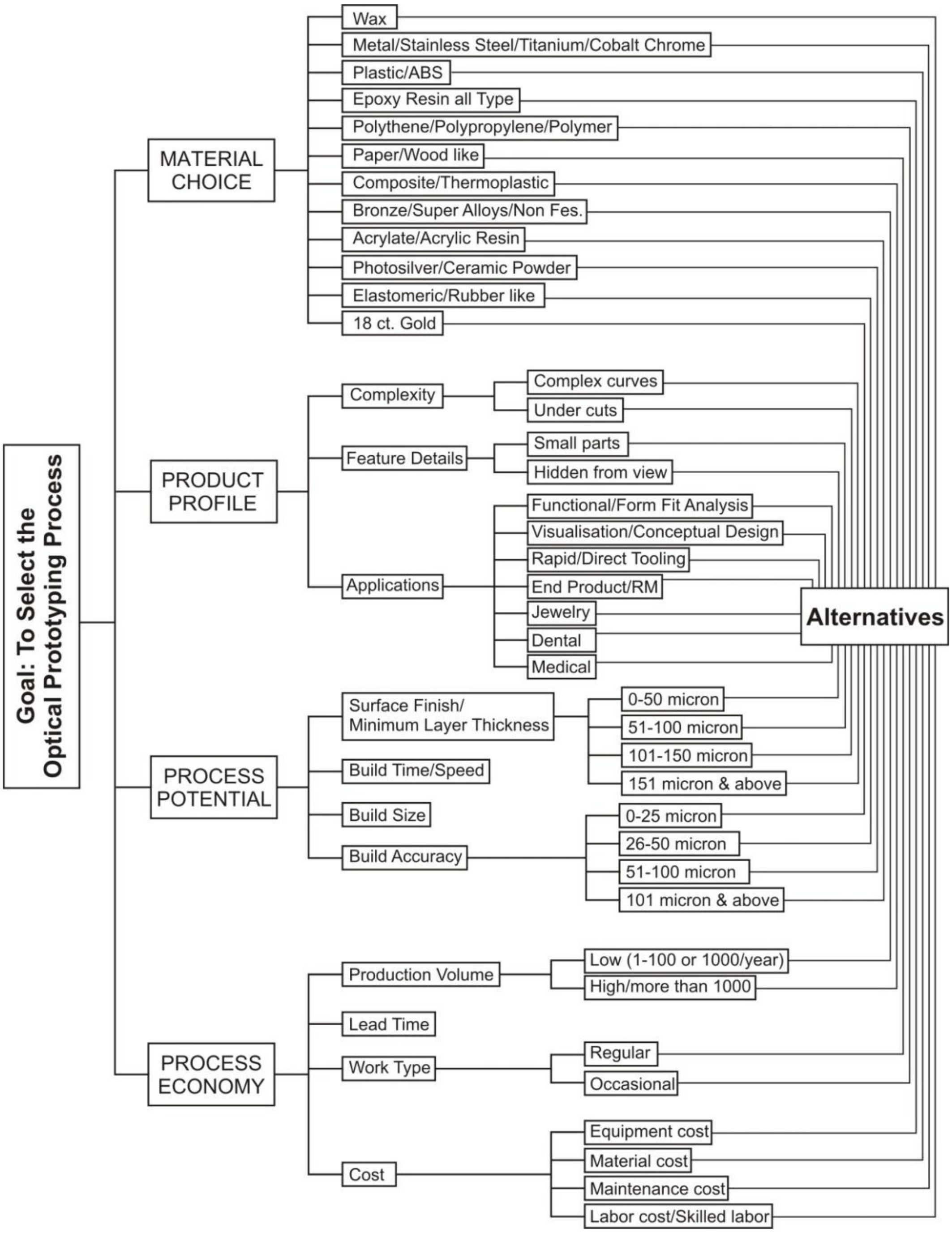


Figure 4.4: RP Based Technology Selection Framework

To unravel the problem of the technology selection process, a Multi Criteria Decision Making (MCDM) technique called Analytical Hierarchy Process (AHP) is used to:

- Assist in a decision making process, where conflicting, qualitative and quantitative attributes are present.
- Develop a system, which is applicable in all scenarios regardless of the size of the company.

An AHP based decision support system has been developed to ease the RP technology selection process. The framework developed in Fig 4.4 will serve as an input to the DSS. It is pertinent to explain the salient features of AHP first to show its effectiveness for RP selection.

4.2.3.2 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process developed by Thomas Satay (1980) at the Wharton Business School, assists the decision makers in the modelling of an intricate problem in a hierarchical structure, displaying the relation of goal, objectives, sub-objectives and alternatives (Lee, 2010). The AHP integrates judgments and personal values in a logical way, the same way the human mind sorts through multiple options in the course of decision making (Gad El Mola et al., 2006). “The strength of the AHP approach lies in its competency to build a complex, multi-attribute, multi-person and multi-parity problem; it can also handle both qualitative and quantitative data. Pairwise comparison can be made using a scale which indicates the intensity with which one element dominates with respect to a higher level element” (Tiwari & Banerjee, 2001). According to Saaty (1990) the most creative part in making a decision is to choose the factors that are pertinent for that decision. In AHP, these attributes are arranged to descend from an overall goal to criteria, sub criteria and alternatives in successive levels. Vaidya and Kumar (2006) described the AHP as an Eigen Value approach to pairwise comparison and explained that the key steps of AHP are:

- State the problem.
- Expand the objectives of the problem or consider all factors, objectives and its aftermath.
- Identify the criteria that can impact the main objective.
- Structure the problem in the form of a hierarchy, starting from goals, main criteria, sub criteria and possible alternatives.

- Comparison of each element with the one above in the hierarchy and its calibration numerical scale. This requires n(n-1)/2 comparisons, where n is the total number of elements.
- Calculations to find maximum Eigen value, Consistency Index CI, Consistency Ratio CR and normalized value for every criteria or alternative.
- If the max Eigen value, CR and CI falls under the specified limits then the decision is made on the normalized value, otherwise the process is repeated until the values fall under the desired limit.

Saaty (1990) developed a 1-9 scale shown in Table 4.1, which is used to provide a degree of preference of one criterion over the other.

Table 4.1: The Fundamental Comparison Scale (Saaty, 1990)

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed
Reciprocals	If activity*i* has one of the above numbers assigned to it when compared with activity*j*, than *j* has the reciprocal value when compared with *i*	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

Ishizaka and Labib (2009) explained in detail the calculation process as after completing the comparison matrices, the priority calculation process begins. “A consistent matrix with known priorities Pi, have comparison of the alternatives i and j is given by pi/pj, multiplied by the priority vector $\vec{P}$ results in,

$$\begin{bmatrix} \lambda_1/\lambda_1 & \lambda_1/\lambda_2 \dots \lambda_1/\lambda_n \\ \lambda_2/\lambda_1 & \lambda_2/\lambda_2 \dots \lambda_2/\lambda_n \\ \dots & \dots \\ \lambda_n/\lambda_1 & \lambda_n/\lambda_2 \dots \lambda_n/\lambda_n \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \dots \\ \lambda_n \end{bmatrix} = n \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \dots \\ \lambda_n \end{bmatrix} \quad (4.1)$$

It can be grouped as:

$$A\vec{\lambda} = n\vec{\lambda},$$

where:

$$\vec{\lambda} = Vector\ of\ Priorities,$$

$$n = Dimension\ of\ the\ Matrix,$$

A = Comparison Matrix.”

According to Saaty (1980) for comparisons of five or more criteria/alternatives the pairwise comparison should be consistent and a measure of inconsistency can be considered by calculating the Consistency Index (CI) and Consistency Ratio (CR) where,

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (4.2)$$

where:

$$\lambda_{max} = Maximum\ Eigen\ Value,$$

and CR = CI/RI,

where RI = Random Index.

Saaty (1980) proposed that a value of 0.10 or less for CR should be acceptable and if the value is more than that, then the analysis is required to be performed again. The calculated RI values are shown in Table 4.2.

Table 4.2: Random Indices (Saaty 1977)

n	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Once the CI and RI have been calculated, the last step is to determine the global priority by synthesizing the local priorities. The AHP employs an additive aggregation with normalization of the sum of local priorities to unite Ishizaka and Labib (2009), given by,

$$P_i = \sum_j w_j . l_{ij} \tag{4.3}$$

Where:

P_i = global priority of alternative *i*,

l_{ij} = local priority,

w_j = weight of the criterion *j*.

The last step of the AHP process is the sensitivity analysis, where priorities are changed marginally, and its impact on the result is monitored. If the output remains the same the results are considered to be accurate.

Due to the limitations of the human judgement ability, particularly during the complex selection process, it is almost impossible to choose the right equipment, where tens of alternatives with a multitude of criteria are available. AHP is a great tool to assist in the selection process.

4.2.3.3 Expert Choice (EC) for Decision Support System Development for RPT Selection

By pairing the scholarly resources of users with the abilities of computers, decision support systems (DSS) are anticipated to increase the excellence of decisions (Forgionne, 1999).

A large number of available criteria along with a great range of available alternatives need computer intervention to expedite the decision making process.

Expert Choice (EC) is the microcomputer software implementation of AHP. EC has been used in a large number of AHP applications, for the decision making problems. A few steps involved in Expert Choice based DSS developments were,

- Building the complete model by entering the objectives and the required criterion for decision making.
- Enter the number of alternatives in alternative panes.
- Create an information document to provide information at every step.

- Pairwise comparison between the criteria down to alternatives.
- Synthesis of results after calculating priorities.
- Sensitivity analysis to verify the results.
- Rating formulas development to accommodate large number of alternatives.

One of the great challenges in RPT selection explained in Chapter 3 is the limited ability to comprehend the intricacies of RP. Due to this reason, rating of alternatives by the user is not possible and requires a system which only takes user input on the defined criteria and provides the selection result. To develop the knowledge base of the DSS, each RP equipment requires data against fifty four selection criteria defined in section 4.2.3.1. To get the information which was not available on the web, a cover letter (Appendix E) along with a questionnaire (Appendix F) was sent by mail to 24 RP manufacturers around the world. Resellers were also contacted by phone and e-mails in different geographical locations. In this way, the required information which was not available elsewhere was able to be obtained. The developed DSS included more than 80 commercially available RP systems worldwide up to June 2012.

A comparative study was conducted by Zapatero et al. (1997) to ascertain how various features of the multi-attribute packages are perceived by decision makers. Five software packages referred to as MCDM were evaluated. They include Expert Choice, Criterion (both AHP based), Logical Decision, VIMDA and VISA. The results showed that Expert Choice was ranked first in user-friendliness and also received the highest score for confidence in the procedure.

4.2.4 SPECIFY/Impact Assessment

Once the external market analysis, operational deficiencies, priorities and selection of the technology have been completed, the next critical step is the assessment of the likely impact of the selected technology on the manufacturing strategy, business and operational performance. This step can also be useful for a company to redefine its strategies for better alignment with the market and customer demands. A detailed analysis of a product development project is suggested to quantify the impact of RP on the project in terms of time and cost. The human resource requirements including training can also be defined at this stage. Assessment of the risk is also proposed to anticipate any risk, uncertainties or threats associated with the new technology. This step is very crucial as SMEs face many hidden issues which must be uncovered before any formal technology related decision is taken. The cycle continues even after deployment of the technology and suggests regular expert review to accommodate the changing market requirements. This will ensure the business synchronizes with changing market and technological capabilities.

4.3 RPT Adoption Framework Implementation

To understand the implementation of RP technology in industrial case studies, the flow chart shown in Figure 4.5 will assist to guide and understand the entire operationalisation process.

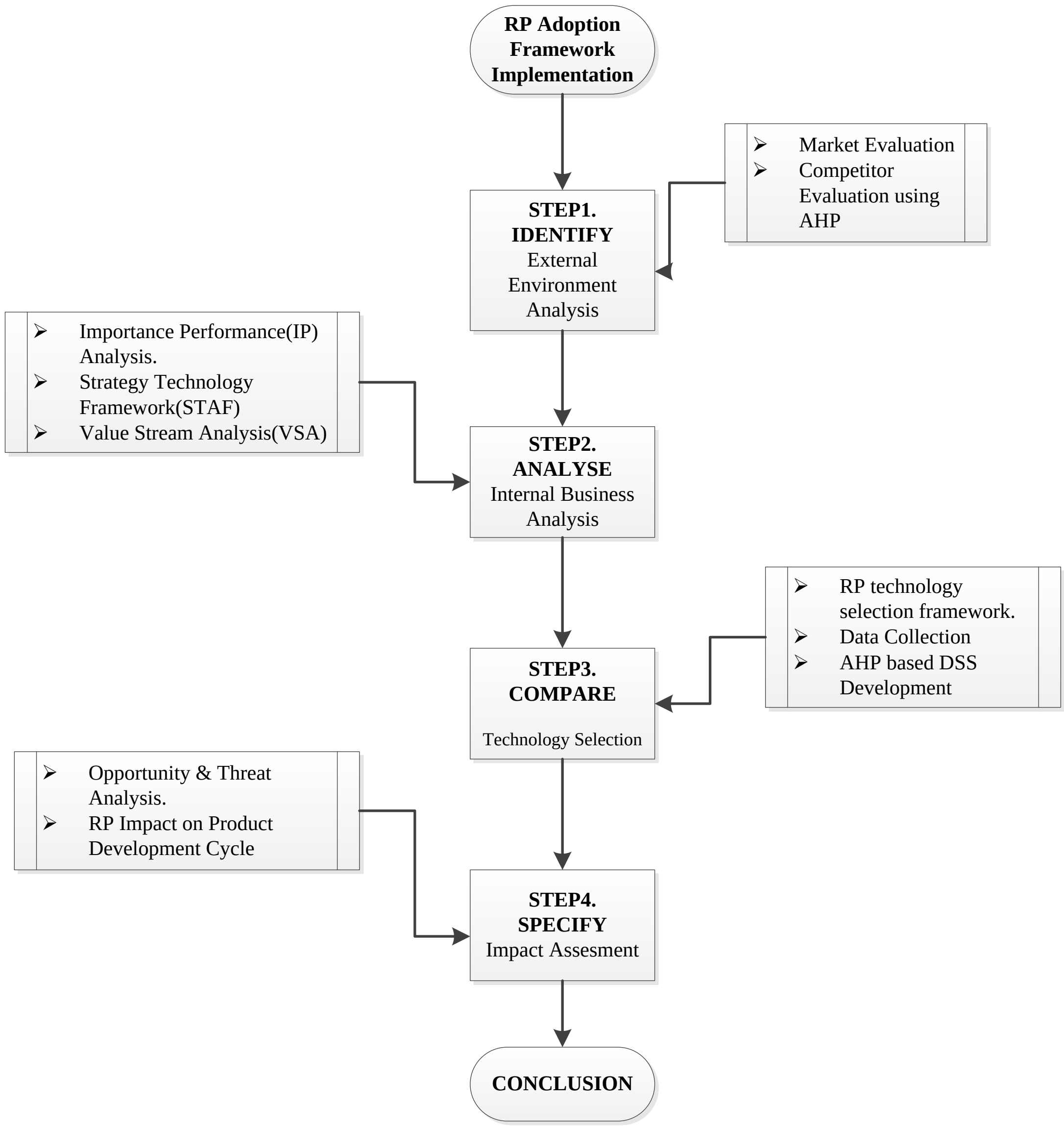


Figure 4.5: RPT Operationalisation Flowchart

4.4 Concluding Remarks

The chapter has explained in detail all the required information for the operationalisation of the RP technology adoption framework. It started from the RPT adoption framework development and formulated the complete operationalisation procedures. This includes the development of the system for Market and Competitor Evaluation, analysis of internal business functions, analysis of product value chain, Decision Support System development for technology selection and impact assessment. The entire development and implementation was established with a specific focus on RP technology and by considering the capabilities of SMEs.

The next chapter will present the complete case study which will not only explain the implementation but also illustrate the impact the technology can have on the business and will also highlight the way product development is carried out particularly in developed countries.

Note: Some of the sections in this chapter have already been published in following papers of the author

Ahmad A, Mazhar MI, Howard IM (2012), ‘A framework for the adoption of Rapid Prototyping for SME’s: From Strategic to Operational International Journal of Industrial Engineering: Theory Applications and Practice, Vol.19 Issue 3, pp. 161-170.

Ahmad A, Hasan M, Erik J (2009), ‘A Strategic Framework & Key Drivers for RP Adoption. *The 33rd Rapid Prototyping Symposium 22-23 June.* Tokyo. Japan.

5

CASE STUDY

This chapter considers the application of the developed RPT adoption framework along with developed tools, frameworks and techniques in real case scenario. This requires an active involvement of the practioners with a vast experience of not only manufacturing operations but also a deep knowledge about markets, customers and competitors. The case study methodology is a proactive approach designed to break the status quo by exposing the role RP can play and by devising the practical solutions to minimize the adoption barriers. Two companies A and B discussed in Chapter 3 participated actively after realizing the impact of the study on their business in particular and on SMEs in general.

5.1 RPT Adoption Framework Germane for Company A and B

A diversified range of products requires efficient manufacturing processes which must be capable of responding efficiently. Time to market and a product which truly satisfies the customer demands ultimately puts pressure on the product development process. To attain the required product with all specifications and manufactured on time necessitates the use of the advanced technology that can provide a competitive edge. Since the product development process is the key to success, Company A was considered appropriate for the RPT adoption implementation process. This Company was not using any RP system and was unfamiliar about the presence of such technology, which made it an ideal candidate for the RPT adoption process to observe what challenges they are facing and the RP capability to tackle these issues. Since it was observed that SMEs reliance on documented procedures and on any formal evaluation systems is minimal most of the decisions are taken by a few people, based on their perceptions and the experience they inherited. This practice hides many critical issues and companies can either lose direction, or if they know the destination, often have no idea as to how to reach there. These issues make the RPD adoption implementation process an ultimate candidate for such companies. Value Stream Analysis was conducted in this Company to quantify the impact of the technology and to see how much impact RP can have at every stage of the product development process. The next section describes the manufacturing operations of company A for an effective understanding of the VSA process. After researching the company, the following became clear;

- Product Development/Management Department: A core team responsible for customer interaction, translating customer requirement into the production, manufacturing capacity determination and planning was normally carried out by the CEO and General Manager Operations. The core team had available support from the Production Manager and his team of Marketing & Finance departments.
- Manufacturing Facility: The manufacturing facility was around 30 kms from the Head office and the staff travelled on a daily basis from the head office to the plant.
- Telecom Shelters: In 2004, new telecom licenses were issued to many international and local companies by considering the expanding requirements in the telecom sector. New market opportunities were generated for the suppliers. Before 2004 all of the shelters were important. By looking at the expanding markets company A shifted focus from fiber glass to MS shelters to get a largest portion of the market share.

Manufacturing Operations: Once the initial design has been approved the manufacturing operation starts with the production of dyes and moulds. The material used is normally wood. Bending of Mild Steel (MS) sheets to get the desired shape is normally carried out manually. Male and female parts of the sheets panels are joined together and high pressure polyurethane foam is inserted to gain thermal insulation. Floor panels are made from cardboard.

Once the outer structure was completed, the assembly process continued to join the roofing and floor. Camlock was added to the assembled structure along with insulations and painting was done where required. Figure 5.1 shows a complete shelter diagram where a few design layers containing some critical information were removed to show the original design.

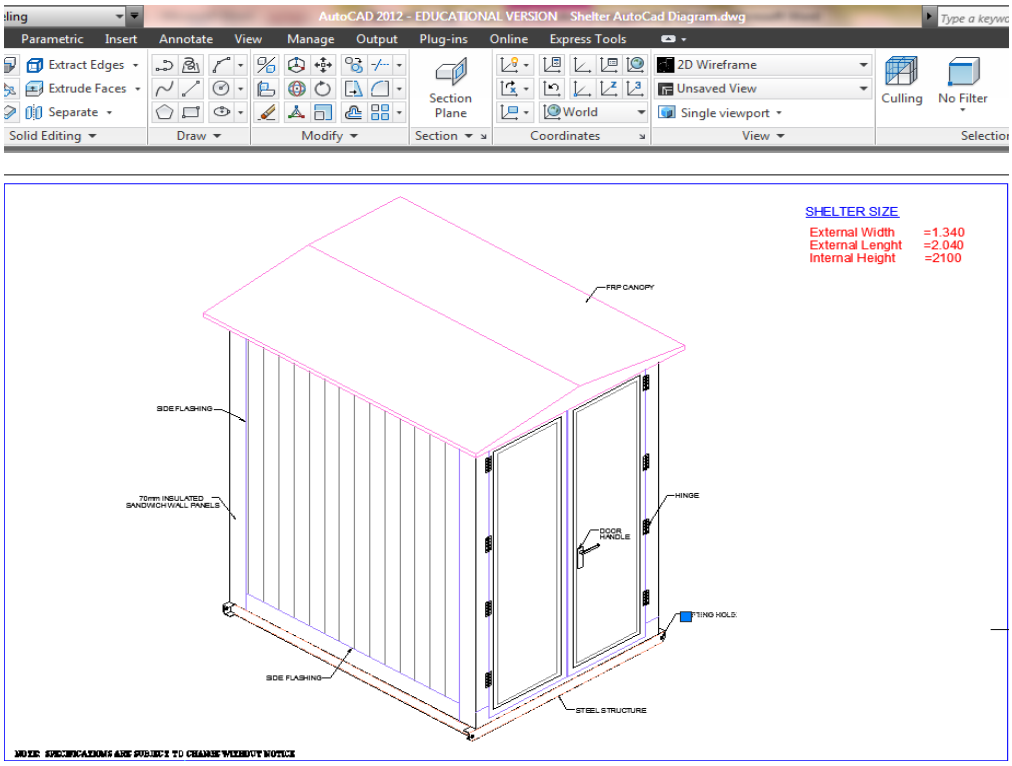


Figure 5.1: Telecom Shelter Diagram – Company A

Other CAD drawings showing detailed representations of all the critical parts were also provided by the company for the analysis purpose only and are not shown in the text. Appendix G shows a complete list of parts used during the prototyping and manufacturing phase. Total number of parts used for a complete shelter was around 222 as mentioned by the Design Engineers. This information will assist to understand the intricacy of the product development process and potential impact of RP on the process.

As the shelter is built into modules, the intrinsic strength of the panels with additional reinforcement from the floor panels made it easy to customize the size of the shelter and assist with a quick installation regardless of the type of the location.

Company B is involved in many diversified operations due to different market and customer requirements. The requirements vary from a very standard market to catering for novel customer demands. For the analysis purpose a major product of the company was selected. Based on that product the market evaluation, competitor analysis and IP analysis was performed. The nature of the product is not disclosed throughout the case study for the anonymity purpose and to minimize any possibility which can lead towards the identification of the company.

5.2 RP Adoption Framework Implementation

As mentioned in section 4.2, the operationalisation/implementation process consists of four processes that assist to develop a complete practical roadmap, capable of providing complete adoption solution from strategy to operational level. The other main purpose is to demonstrate the technology strategy linkage, identifying RP impact and to generate a comprehensive documented technology adoption process. All the four stages of the operationalisation are explained in coming sections.

5.3 IDENTIFY/External Environment Analysis

The external environment analysis consists of the market and competitor evaluation. As an input to this phase, the purpose of the whole study including RP technology benefit and the possible impacts on SMEs were explained in detail to the business and technical managers of both companies. The importance of adopting the external evaluation approach along with tools was explained in detail and concerns and queries were sorted out at this very initial stage. The managers were also briefed regarding the criteria selected for competitor and market evaluation. The numbers of steps involved during this phase are,

a) Market Evaluation of both company A & B.

b) Competitor Analysis of company A & B. Company A identified three competitors (Company 1, 2 & 3) whereas Company B recognised two competitors (Company 1 & 2).

Market Evaluation Questionnaire (Appendix C) was given to managers of both companies, to take an overview regarding the customer and market demands. The response of both companies is shown in Table 5.1.

Response from both companies in developing (A) and developed (B) economies clearly indicates the challenges they are facing. There are considerable similarities regardless of boundaries e.g. both are facing turbulent markets where standardization levels are medium-high whereas both type of customers expect flexibility. Time to market and increased market share is a common challenge. In both companies technology plays a critical role but formal procedures for selection of the technology are absent in company A, whereas they are partially present in company B. A manufacturing audit process which links the business strategy and goals, with the business operations with technology, surprisingly did not exist.

Table 5.1: Company A and B Market Evaluation Response

	Criterion	Response	
		Company A	**Company B**
1)	Nature of Market	Medium Standardization	Medium Standardization – Differentiation
2)	Product Customization Level	Moderate	Moderate – High
3)	Product Complexity Levels	Medium	High
4)	Product Flexibility Demand	Moderate	Moderate – High
5)	Time to Market Requirement	High	Moderate – High
6)	Market Condition	Turbulent	Turbulent
7)	Product Volume Demands	Medium	Single Unit – High
8)	Most Important Business Outcome	Increased Market Share	Increased Market Share along with Lead Time reduction and Quality with Low Price
9)	Role of Technology	Critical	Critical
10)	Technology Selection Procedures	No Formal Process	In house and Customer reviews, capability analysis etc.
11)	Critical Technology Selection Parameters	Return on Investment	Benchmarking Functional Requirements
12)	Document Procedures for Product Development	No	ISO 9000 Certified
13)	Formal Manufacturing Audit in Place?	No	Only at CEO & CFO Level

When this was further clarified with Company B, the response was that the CEO and CFO looked at these matters but it was agreed that they only look at strategic parameters and the formal evaluation process of linking strategy with technology does not exist.

Once the nature of market demands and customer expectations were made clear, the next step was the competitive position modelling to see how well the companies were performing against their competitors. The numbers of steps involved in this process include;

a) Problem Modelling: To identify the goal, main objectives & sub objectives and assemble them in a hierarchy.

b) Pairwise Comparison of Criteria against the goal: To determine the weights of every objective and sub objective against the goal.

c) Competitor Rating: Rating of competitors against the objective and sub objectives.

d) Synthesis: To obtain the synthesized value of each criterion, to determine the final ranking of each company.

The above steps are explained in coming sections.

5.3.1 Problem Modelling

The first part of the competitor evaluation was to assemble the goal, criteria, sub criteria and the number of competitors in a hierarchical view for the evaluation purpose as shown in Figure 5.2. This has four main objectives named competitor objectives, assumption, strategy and ability. Each main objective has further sub-objectives.

Model Name: Competitor Evaluation Company A

Treeview

- **Goal: Evaluation of Competitors**
  - **Objectives**
    - **Financial position**
    - **Market Share**
    - **Technology Leadership**
  - **Assumption**
    - **Belief about competitive position**
    - **Past experience with the product**
    - **Industry Trends**
  - **Strategy**
    - **R&D Projects**
    - **Capital Investment**
    - **Strategy**
    - **Strategic Partnership**
  - **Capability**
    - **Technological Capability**
    - **Operational Performance**
    - **Capability**
    - **Product Quality**

Alternatives

COMPANY1
COMPANY2
COMPANY 3
ALPHA/COMPANYA

Figure 5.2: Competitor Evaluation Hierarchy

5.3.2 Pairwise Comparison of Criteria with respect to the Goal

Since all the criteria defined in the hierarchy cannot have equal weightage for a company, so it is important to calculate the priority of each criteria against the defined goal. In other words, to determine the amount of weight each goal or sub-objective records in achieving the ultimate goal. Managers were asked to compare first the objectives with respect to the goal and then pairwise comparison was made of each sub objective against one at a higher level on the node. A complete weighted hierarchy is shown in Figure 5.3.

Model Name: Competitor Evaluation Company A

Treeview

- **Goal: Evaluation of Competitors**
  - **Objectives (L: .219)**
    - **Financial position (L: .466)**
    - **Market Share (L: .316)**
    - **Technology Leadership (L: .218)**
  - **Assumption (L: .147)**
    - **Belief about competitive position (L: .281)**
    - **Past experience with the product (L: .371)**
    - **Industry Trends (L: .348)**
  - **Strategy (L: .375)**
    - **R&D Projects (L: .234)**
    - **Capital Investment (L: .210)**
    - **Strategy (L: .256)**
    - **Strategic Partnership (L: .300)**
  - **Capability (L: .259)**
    - **Technological Capability (L: .194)**
    - **Operational Performance (L: .257)**
    - **Capability (L: .345)**
    - **Product Quality (L: .204)**

Figure 5.3: Weighted Hierarchy of Competitor Evaluation; Company A

5.3.3 Competitor's Rating

Once the ranking of the criterion was obtained, the next step was to rate competitors against the defined criteria to see how they were performing. The managers were asked to rate each competitor on a 1-7 scale against each criterion, where 1 was poor and 7 was extremely good. The ratings achieved during this process are shown in Table 5.2.

Table 5.2: Company A Competitor's Rating

	Critical Success Factors	Company 1 Rating	Company 2 Rating	Company 3 Rating	Company A Rating
1)	Financial Position	6	5	4	5
2)	Market Share	6	5	3	5
3)	Technology Leadership	5	5	3	5
4)	Belief about Competitive Position	6	4	3	4
5)	Post Experience with the Product	5	4	3	4
6)	Industry Trends	6	5	4	3
7)	R&D Projects	5	4	3	3
8)	Capital Investment	6	5	4	4
9)	Promotional Campaign	4	3	4	4
10)	Strategic Partnership	1	1	1	1
11)	Technological Capability	5	5	3	5
12)	Operational Performance	6	5	4	7
13)	Product Acceptance	6	5	4	5
14)	Product Quality	6	5	4	6

The next step was to create a rating scale formula. The purpose was to assign numerical values and to compare alternatives against a standard scale. Each company was rated against every single criterion on the defined standard scale. Rating of companies against four main objectives is shown in Figure 5.4 for illustration purposes.

AID	Alternative	Total	RATINGS Competitor Assumption Past experience with the product (L: .371)
A1	COMPANY1	.663	.660
A2	COMPANY2	.523	.490
A3	COMPANY 3	.379	.330
A4	ALPHA/A COMPANY	.470	.490

AID	Alternative	Total	RATINGS Competitor Assumption Industry Trends (L: .348)
A1	COMPANY1	.663	.830
A2	COMPANY2	.523	.660
A3	COMPANY 3	.379	.490
A4	ALPHA/A COMPANY	.470	.330

AID	Alternative	Total	RATINGS Competitor Strategy R&D Projects (L: .234)
A1	COMPANY1	.663	.660
A2	COMPANY2	.523	.490
A3	COMPANY 3	.379	.330
A4	ALPHA/A COMPANY	.470	.330

AID	Alternative	Total	RATINGS Competitor Strategy Capital Investment (L: .210)
A1	COMPANY1	.663	.830
A2	COMPANY2	.523	.660
A3	COMPANY 3	.379	.490
A4	ALPHA/A COMPANY	.470	.490

Figure 5.4: Ratings of the Competitors against Defined Criteria

5.3.4 Synthesis

Once the pairwise comparison and rating of alternatives was completed, the next step was the synthesis which was done by multiplying each ranking by the priority of its criteria or any related sub-criteria. The complete synthesis values obtained are shown in Figure 5.5.

Level 1	Level 2	Alts	Prty
Competitor Objectives (L: .219)	Financial ...	COMPAN...	.023
		COMPAN...	.019
		COMPAN...	.014
		ALPHA/A ...	.019
	Market Sh...	COMPAN...	.016
		COMPAN...	.013
		COMPAN...	.007
		ALPHA/A ...	.013
	Technolog...	COMPAN...	.010
		COMPAN...	.010
		COMPAN...	.005
		ALPHA/A ...	.007
Competitor Assumption (L: .147)	Belief abo...	COMPAN...	.011
		COMPAN...	.006
		COMPAN...	.004
		ALPHA/A ...	.006
	Past expe...	COMPAN...	.012
		COMPAN...	.009
		COMPAN...	.006
		ALPHA/A ...	.009
	Industry T...	COMPAN...	.013
		COMPAN...	.010
		COMPAN...	.008
		ALPHA/A ...	.005
Competitor Strategy (L: .375)	R&D Proj...	COMPAN...	.021
		COMPAN...	.015
		COMPAN...	.010
		ALPHA/A ...	.010
	Capital In...	COMPAN...	.019
		COMPAN...	.015
		COMPAN...	.011
		ALPHA/A ...	.011
	Promotion...	COMPAN...	.020
		COMPAN...	.014
		COMPAN...	.020
		ALPHA/A ...	.000
	Strategic ...	COMPAN...	.000
		COMPAN...	.000
		COMPAN...	.000
		ALPHA/A ...	.000
Competitor Capability (L: .259)	Technolog...	COMPAN...	.010
		COMPAN...	.010
		COMPAN...	.005
		ALPHA/A ...	.010
	Operation...	COMPAN...	.014
		COMPAN...	.011
		COMPAN...	.008
		ALPHA/A ...	.017
	Product a...	COMPAN...	.020
		COMPAN...	.016
		COMPAN...	.012
		ALPHA/A ...	.016
Competitor Capability (L: .259)	Product Q...	COMPAN...	.012
		COMPAN...	.009
		COMPAN...	.007
		ALPHA/A ...	.012

Figure 5.5: Synthesis of Competitor Evaluation

Determination of the global priority was the last step which was achieved by synthesis of all local priorities. The traditional AHP approach uses an additive aggregation with normalization of the sum of the local priorities to unity (Ishizaka et al, 2009) using the formula,

$$P_i = \sum_j w_j . l_{ij} . \tag{5.1}$$

The final ranking of the alternatives based on the above calculations is shown in Figure 5.6.

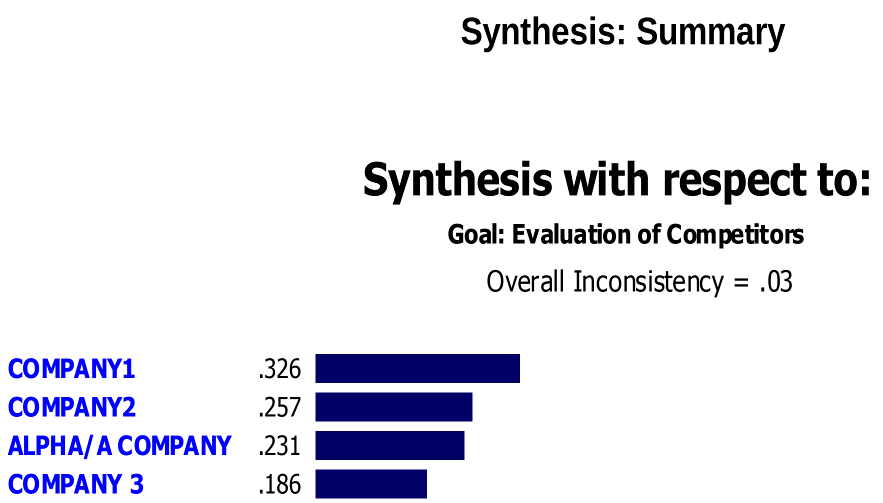


Figure 5.6: Competitors Ranking Results

The overall inconsistency of the evaluation process was 0.03 which is well below the Saaty acceptable value of 0.1, meaning that any value below 0.1 shows that the analysis was consistent and valid. The results show that the process is consistent and clearly highlights the overall position of the company with respect to its customers. The figure 5.6 shows the overall ranking of Company A to be 0.231 as compared to its three competitors. The company’s position against any objective or sub objective can also be obtained, to see how well the company is performing on any single criteria.

Similar analysis was carried out for company B. The managers identified two companies as major competitors and the ranking of the companies is shown in Table 5.3.

Table 5.3: Company B Competitive Rating

	Critical Success Factors	Company 1	Company 2	Company B
1)	Financial Position	5	5	3-5
2)	Market Share	5	2-3	3
3)	Technology Leadership	5	2	3-4
4)	Belief about Competitive Position	6	3	5
5)	Post Experience with the Product	6	6	3
6)	Industry Trends	5	2	5
7)	R&D Projects	5	2	5
8)	Capital Investment	5	2	5
9)	Promotional Campaign	5	3	2-3
10)	Strategic Partnership	5	2	5
11)	Technological Capability	5	2	5
12)	Operational Performance	3	2	3-5
13)	Product Acceptance	3	2	2-3
14)	Product Quality	2-3	2	2-3

Analysis similar to Company A was carried out which included the pairwise comparison of the critical success factors to obtain the preference rating, according to the company B perspective. Rating formulas were developed and synthesis was done to see the competitive position of company B. Figure 5.7 shows the ranking of the factors and company B ratings obtained after synthesis.

Model Name: Competitor Evaluation Company B

Treeview

- **Goal: Evaluation of Competitors**
  - **Objectives (L: .425)**
    - **Financial position (L: .565)**
    - **Market Share (L: .288)**
    - **Technology Leadership (L: .148)**
  - **Assumption (L: .112)**
    - **Belief about competitive position (L: .151)**
    - **Past experience with the product (L: .550)**
    - **Industry Trends (L: .299)**
  - **Strategy (L: .292)**
    - **R&D Projects (L: .258)**
    - **Capital Investment (L: .169)**
    - **Promotional Campaign (L: .101)**
    - **Strategic Partnership (L: .472)**
  - **Capability (L: .171)**
    - **Technological Capability (L: .096)**
    - **Operational Performance (L: .273)**
    - **Product acceptance (L: .476)**
    - **Product Quality (L: .155)**

Alternatives

COMPANY1	.463
COMPANY2	.158
BRAVO/COMPANYB	.379

Figure 5.7: Company B Attribute Ranking & Competitor Evaluation

Step 1 of the framework analysed the External Environment in detail and at this stage, what the market and customer demands and where the companies stand against its competitors was very clear to both companies. The next section will analyse the internal operations.

5.4 ANALYSE/Internal Business Analysis

This step involves several aspects to observe the ability of current processes/ operations and technology to deliver the required outcomes which resulted from the External Environment Analysis. The three main parts of this step are;

- Importance Performance Analysis

- Strategy Technology Alignment
- Value Stream Analysis (VSA)

These steps are explained in detail in coming sections.

5.4.1 Importance Performance (IP) Analysis

IP analysis is used to understand how well Company A is performing against the critical success factors. Thirty three criteria shown in Table 5.4 were determined through literature and expert discussions to be important for product development programmes. These were the areas where RP is capable of influencing the outcome. Both Production and General Managers of Company A were invited to discuss the IP analysis questionnaire provided in Appendix D and ratings were obtained on nine points on the important and nine points on the performance scale (Appendix C). They were asked to rank each criteria based on the degree of importance and rank how well the company is performing against the same criteria.

Table 5.4: Criteria for Important Performance (IP) Analysis

1) The Cost Effective Customization ability of the company	18) Design freedom
2) Differentiation/process flexibility	19) Assembly cost
3) Time to Market	20) Tooling cost
4) Fast Response	21) Time to market cost
5) After Sale Service	22) Redesign cost
6) Part count reduction	23) Cost of waste
7) Improved production	24) Product return cost
8) Low volume production	25) Supply chain cost
9) Low inventory	26) Better design
10) Reduce cost and operation length	27) Product performance
11) Short Compressed life cycle	28) Rapid new product introduction
12) Increased synchronization	29) Variable order size
13) Low cycle time	30) Quick design modifications
14) Ease in innovation	31) Set up time
15) Reduce computing cost	32) Low direct labour
16) Ease of operation	33) Product development cycle
17) Visual aid for tool maker	

Each question was discussed in both general and specific project contexts. The obtained responses were plotted on an IP diagram as shown in Figure 5.8. The numbers in the diagram are the same numbers provided in Table 5.4.

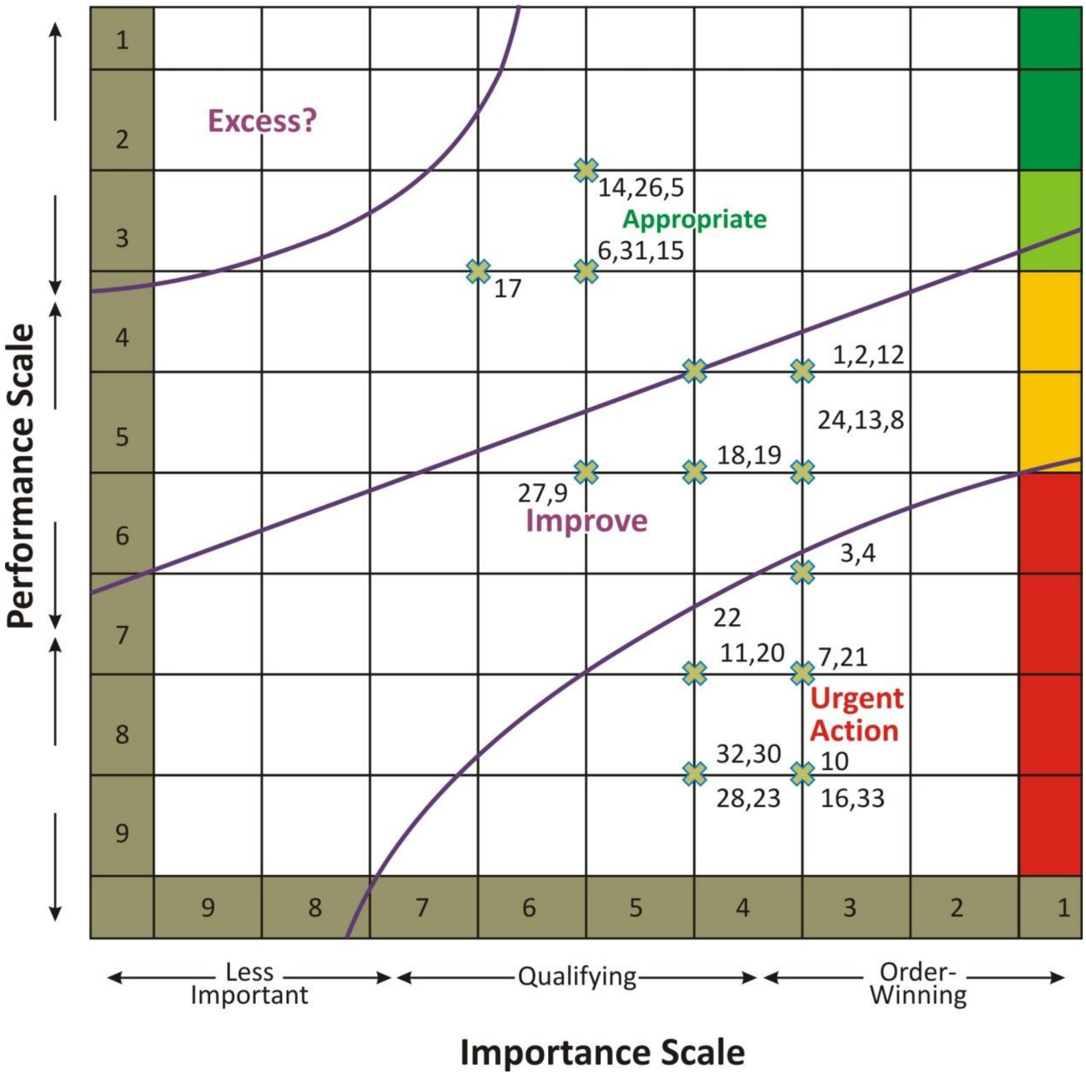


Figure 5.8: Importance Performance Analysis Company A

The IP analysis shown in Figure 5.8 gives a very clear picture of the company's operational performance. The numbers in each zone refer to the numbers mentioned in Table 5.4. The following shall be understood from the analysis;

Urgent Action: Order winning criteria, worse than competitors and markets.

i) Time to Market, Improved Production, Short Life Cycle

ii) Reduce operational length, Redesigning Cost, Ease of operations

iii) Cost of waste, Rapid new production introduction, Quick Design change

iv) Complete product development cycle

Improve: Order winning criteria, similar to competitors but need improvement.

i) Process Flexibility, Cost effective customization, Low inventory

ii) Increased synchronization, Low Cycle Time

iii) Design Freedom, Assembly Cost

iv) Better Product Performance & Product Return

Appropriate: Order Qualifying Criteria same as Competitors

i) Part count reduction, Reduce computing cost

ii) Supply chain cost, Variable order size

iii) Visual aid for tool makers

iv) After sale service

From Figure 5.8, it is clear that time to market, new product introduction and its associated parameters, like quick design and compressed development cycle, are the parameters required for a competitive position but the company was not doing good enough to achieve these targets, which put these factors in an urgent action zone. The other factors like increased synchronization, design freedom and assembly cost are few of the attributes where the company still needs improvement. There were a few factors where the company believed that they are doing better than the competitors which include the supply chain cost, part count reduction and after sales service. The main reasons for this were the cheap labour and availability of standard parts from local markets.

The similar process was repeated for company B. The data received from Company B against the IP analysis questionnaire (Appendix D), was plotted on an Importance Performance Analysis Diagram shown in Figure 5.9. The results obtained from Company B include the followings;

Urgent Action: Order winning criteria, worse than competitors.

- Cost associated with time to market
- Redesign cost
- Supply chain cost
- Low director labour, Product Development Cycle

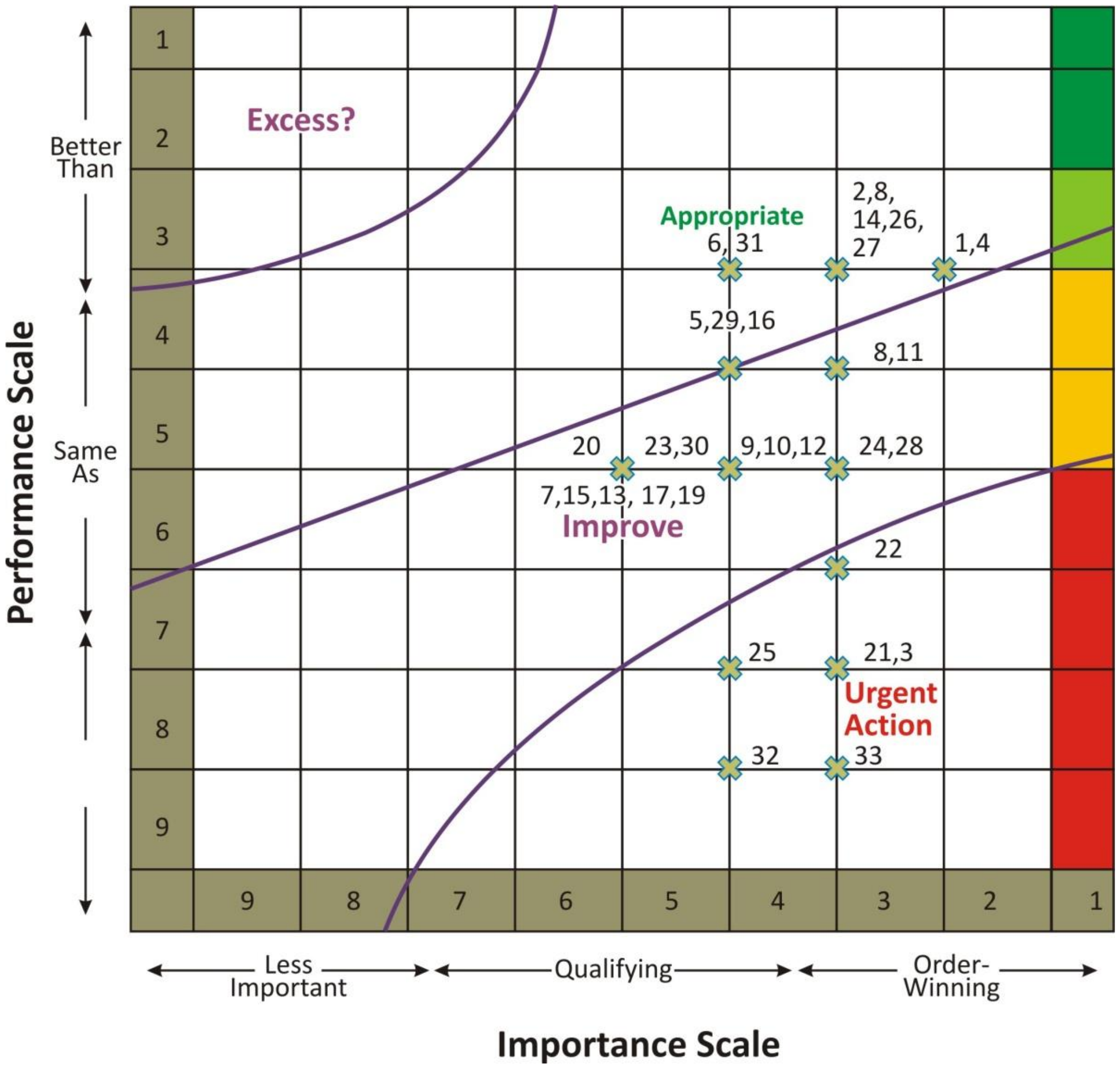


Figure 5.9: Important Performance Analysis Company B

Improve: Order winning criteria, similar to competitor but need improvement.

- Low volume production and inventory, reduce operational length and cost
- Increase synchronization, low cycle time, assembly cost
- Ease of operations, cost of waste
- Production warranty, Rapid new introduction

Appropriate: Order Qualifying Criteria same as Competitors

i) The cost effective customization ability, fast response

ii) Low volume production, ease in innovation

iii) Better product performance,

iv) Setup time, variable order size

For Company B the time to market, labour and supply chain cost reduction along with improved product development cycle are the key order winning factors, where company performance did not match with the required performance levels and required urgent attention. The other factors like ease of operation, increased synchronization, reduced operational length demand improvements.

From IP analysis for both company A and B, it is apparent that the time to market and a compressed product development cycle (which consists of many other functions like improved synchronization, low cycle time etc.) are the common challenges both companies are facing and both are not able to fully comprehend these challenges.

Company B was outsourcing some prototyping models from service bureaus for some of their product development activities, so were able to respond quickly but it increased their supply chain cost and cost of labour is already a big issue in the developed countries. These companies are seeking for a threshold point where they can balance these decisive factors. For Company A, labour and supply chain cost is not a big issue but controlling effectively all the activities related to product development is a great challenge. Introducing products within a short period with great customer acceptance is therefore a common challenge.

At this point, the strategic preferences, operation requirements and deficiencies have been clearly identified.

The next step is the placement of the companies on the developed technology grid to identify any mismatch between the current technology in use and market demands.

5.4.2 Strategy Technology Alignment

Technology plays a vital role in the achievement of business goals. Using the right technology at the right time ensures that the company understands the dynamics of the market and customers and responds appropriately. Any discrepancy between the market demands and company ability can results in loss of market share. The assimilation of business and technology is essential for the top managers, but a methodology for such linkage is missing (Sharif, 1994).

From market evaluation and IP analysis it is evident that Company A is working in an environment where market conditions are turbulent, product customisation levels are high and time to market is low, which demands technology which must be able to reduce operational length, assist in rapid new introduction of products resulting in low time to market. It was revealed during discussions that the company only relies on subtractive (CNC) manufacturing whereas they had no idea about the existence of any technology like RP. This placed them on the developed Strategic Technology Adoption Framework (STAF) at a position suitable for stable markets as shown in Figure 5.10.

Figure 5.10: Company A Positioning on STAF

The stable market position shown in Figure 5.10 can only meet the market which requires moderate customisation along with moderate response. In this part of the grid, time to market is not an issue, so the control on the product development cycle is not an essential criterion.

It is also evident in Figure 5.10 that the current technology is not capable of delivering the issues and the company managers identified through the Market Evaluation and IP analysis exercises. The company's resources that will be used in future to meet market demands will not be able to bring any significant changes. The matrix suggests an upward “Desired” shift, which stresses the use of more advanced technology like RP as most of the issues identified were centred on the product development related activities.

Company B was also facing turbulent markets and has customers varying from single unit to high volume. The IP analysis of company B showed that Time to Market, Redesign Cost and Product Development were the areas that needed urgent attention.

The company was outsourcing a few prototyping services from an overseas bureau. This placed them in a better position on the “Stable Markets” grid. Since the Product Development and Time to Market were still the areas which required urgent attention, this means that current setup/technology was not able to produce the desired outcome. The customer demand varied from low to high volume with very low Time to Market, showing the important consideration of using both Rapid Prototyping and Rapid Manufacturing (RM) technologies for the end production of parts where possible. The current and desired position of company B is shown on the STAF in Figure 5.11.

The next step introduces the product development VSA, which not only validates the technology proposed during placement of the company on STAF, but it also endorses the issues raised during the IP analysis process

Figure 5.11: Company B Position on STAF

5.4.3 Product Development Value Stream Analysis (VSA)

A true understanding of what a company faces in the markets and how its operations respond requires a novel approach, which departs from traditional VSA process. The rationale of this is that despite the use of a simple VSA it was hard to clearly identify aspects of the companies operation that was hidden which actually caused a big mismatch between the market demands and operational performance.

To identify the root causes, a micro VSA was conducted at Company A. The analysis focused on a specific project which involved the design, development, manufacturing and commissioning of telecom shelters for major Telecom Companies in the country. This was an excellent opportunity as it involved all the product development related activities starting from customer requirements through design, prototyping and then on to the manufacturing stage. The first challenge was to gather all documentation regarding this project, starting from the customer requirements identification. Unfortunately the only documents available regarding the project were financial documents. These documents only provided the part lists and any major expenses made during the life of the project. This is a normal practice in SMEs, where only financial details are maintained and all other information is remembered by only a few staff often at the top positions in the company.

The only solution of this problem was extended debriefing sessions with the management to gather all possible information regarding this particular project. The first part of the discussion concerned the rationale for how the product development process was actually carried out for this project. Figure 5.12 shows the complete process of activities and information flow that was obtained for the project.

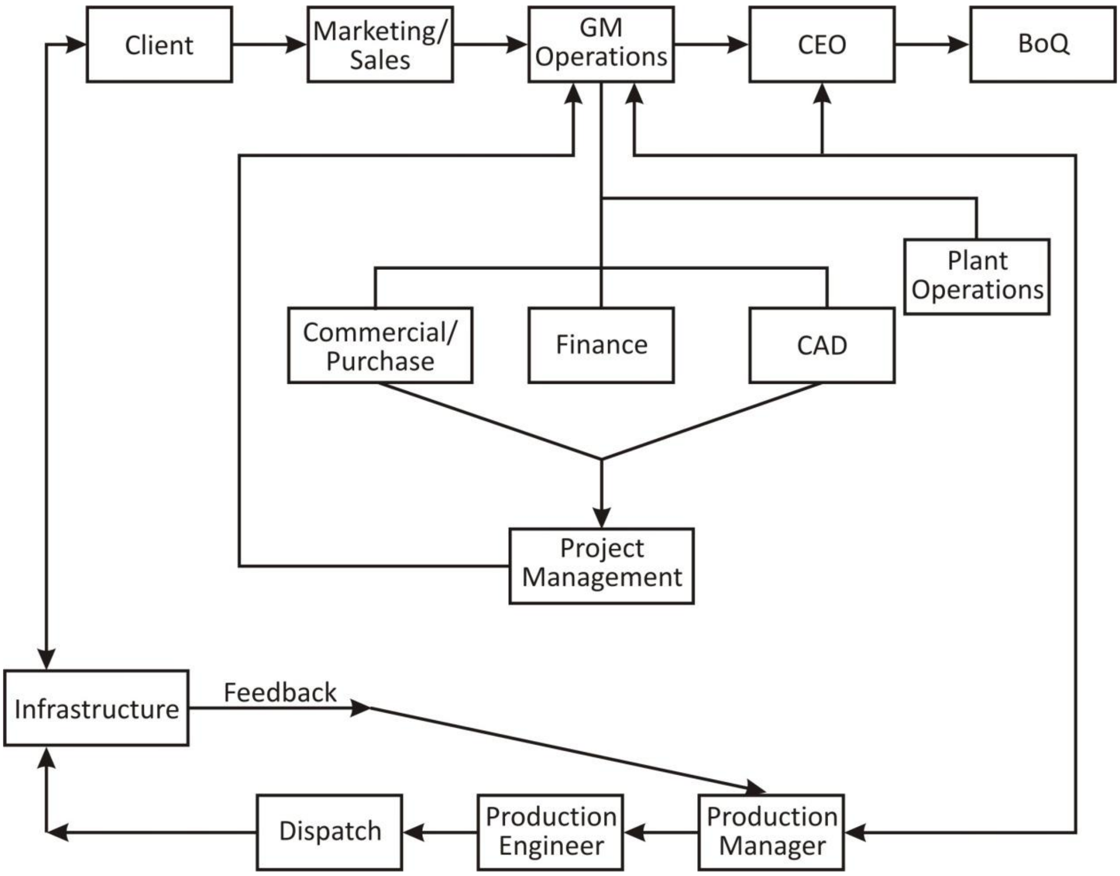


Figure 5.12: Sequence of Information Flow for a Project

The next step was to identify the main activities carried out from the start in identifying client requirements right through to the complete manufacture of the final product. A long list of activities emerged as a result of extensive brainstorming sessions. The activities were grouped into 20 main groups for evaluation purposes and were used as input to the Pro-Time Estimate Programme as shown in Figure 5.13.

			Task	
	ID	Description	Task Index	Ma ch/
1	OTR1	Generation of idea from client	1	Manual
2	OTR2	Marketing contacted client for details	2	Manual
3	OTR3	Visual search of already produced by others	3	Manual
4	OTR4	Initial idea moved to General Manager Operations for initial screening	4	Manual
5	OTR5	Design/Detail documentation devloped	5	Manual
6	OTR6	GM &CEO mmetings and design review discussion	6	Manual
7	OTR7	Verification by CEO	7	Manual
8	OTR8	Design generation on AutoCad	8	Manual
9	OTR9	Verification by client	9	Manual
10	OTR10	Design communicated to manf. and management	10	Manual
11	OTR11	Financial Calculations and Manf. feedback	11	Manual
12	OTR12	Internal Review of Design	12	Manual
13	OTR13	Material Collection from open market for prototyping	13	Manual
14	OTR14	Equipment requirment and developemt for prototyping	14	Manual
15	OTR15	First prototype development	15	Manual
16	OTR16	Clients Arrival and proposed changes	16	Manual
17	OTR17	Design Changes once Manf. started	17	Manual
18	OTR18	Cam Lock Design issue	18	Manual
19	OTR19	Fault detected due to conventional manufacturing system	19	Manual
20	OTR20	R&D Demand for polyurethane injection	20	Manual

Figure 5.13: Shelter Development Sequence of Activities

The project was initiated after the new telecom companies got licences in mid-2004. New market opportunities were then foreseen. Before this time, all the shelters were imported and after receiving licences from the Government, the new market requirements were created and company A shifted its focus to engross a reasonable market share. An imported shelter was studied in detail and clients were contacted to inform them regarding the ability of the company to produce shelters in the local market with an opportunity of installation and maintenance by the Company A. To release the pressure on supply chains and due to the maintenance issues particularly in remote areas, telecom companies informed their requirements. Some of these requirements were the ability to withstand high temperatures and very heavy winds at high altitudes, resistance to earthquakes etc.

Once the major activities were recognized, the next step was to identify all possible factors that had a positive or negative impact on the project.

Around 110 activities were identified from Concept Development to the finished product. These activities are shown in Figure 5.14 and are categorized in 16 groups based on their relevancy.

OTR1 - Generation of idea from client

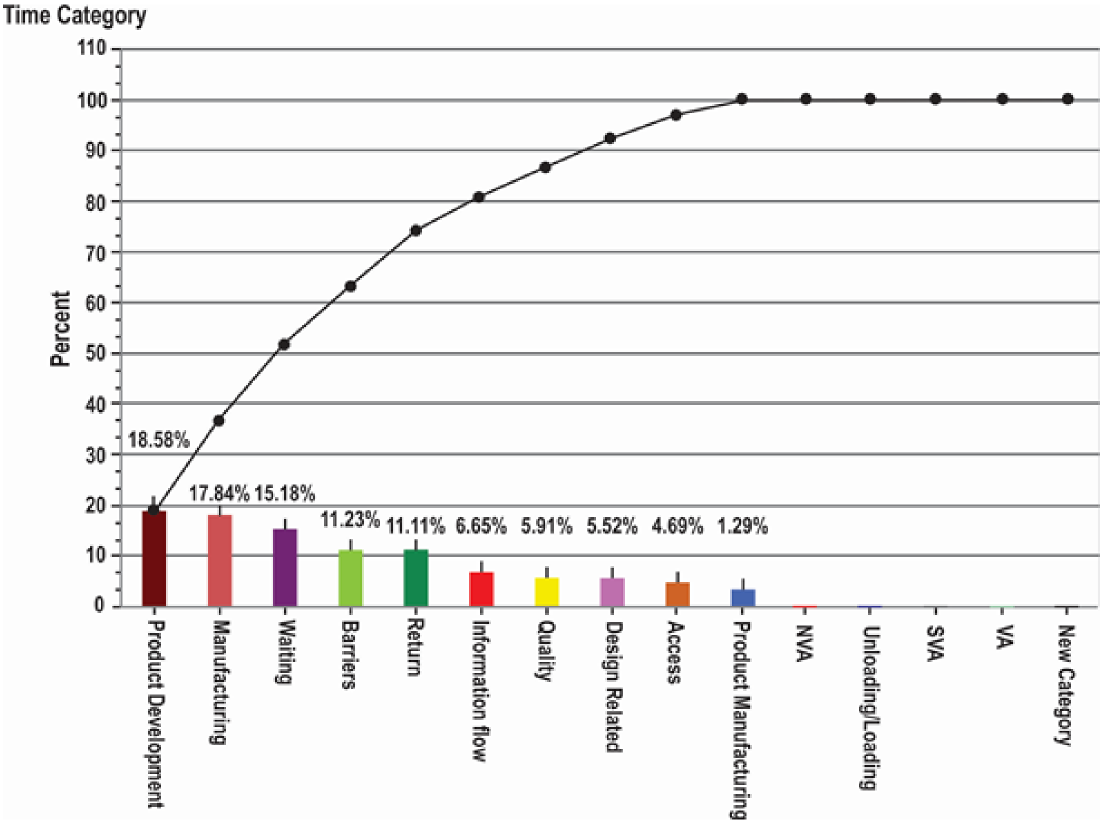
	Category	Detail
1	Information flow	Lack of information
2		Information medium
3		Competence
4		Idea screening
5		Information validation
6		Gathering of information
7		Benchmarking
8	Return	Return due to incomplete information
9		Due to inaccurate design
10		Due to incompatible DFM
11		Due to incompatible DFA
12		Due to non conformance of equipment
13		Return for warranty
14	Waiting	Waiting due to machine cycle time
15		Waiting due to missing material
16		Waiting due to tools
17		Waiting due upstream issue/colleague
18		Waiting due downstream issue/colleague
19		Waiting for missing information
20		Waiting for design amendments
21		Waiting for design finalization
22	Barriers	Behind the wall approach
23		Failure to involve client during design
24		Failure to involve manf. during design
25		Design failures
26	Manufacturing	Cam lock failure
27		Die design issues
28		Mould design issues
29		Injection problems
30		Labor problem
31	Unloading/Loading	Loading machine
32		Unloading machine
33	Access	Prototype assembly
34		Unpacking/Opening
35		Remove excess material
36		Walking to reach waste containers
37		Moving to the factory
38		Disassembling
39	Quality	Quality inspections (Legal obligation/Homologation)
40		Quality proofs (Legal obligation/Homologation)
41		Paper fillings/Decals/Stickers
42		Quality inspections/scanner
43		Quality proofs
44		Paper fillings
45		Design verification
46		Design validation
47		Assembly issue
48	Design Related	Meetings
49		Discussion
50		Cam lock design issues
51		Client arrival
52		Manufacturing feedback
53		Polyurethene filling issues
54		Wall panel linkage issue
55		Floor panel changes
56	Product Development	Collecting required information

OTR1 - Generation of idea from client

	Category	Detail
24	Unloading/Loading	Failure to involve manf. during design
25		Design failures
26	Manufacturing	Cam lock failure
27		Die design issues
28		Mould design issues
29		Injection problems
30		Labor problem
31	Unloading/Loading	Loading machine
32		Unloading machine
33	Access	Prototype assembly
34		Unpacking/Opening
35		Remove excess material
36		Walking to reach waste containers
37		Moving to the factory
38		Disassembling
39	Quality	Quality inspections (Legal obligation/Homologation)
40		Quality proofs (Legal obligation/Homologation)
41		Paper fillings/Decals/Stickers
42		Quality inspections/scanner
43		Quality proofs
44		Paper fillings
45		Design verification
46		Design validation
47		Assembly issue
48	Design Related	Meetings
49		Discussion
50		Cam lock design issues
51		Client arrival
52		Manufacturing feedback
53		Polyurethene filling issues
54		Wall panel linkage issue
55		Floor panel changes
56	Access	Collecting required information
57		Analyzing competitors
58		Cost calculations
59		AutoCad design
60		Design verification
61		Design validation
62		Internal assessment
63		Gluing
64		Inserting
65		Soldering
66		Product identification
67		Flash welding
68		Pretreatment
69		Painting
70	Waiting	Die making
71		Mold making
72		Cam lock design
73		Eq. selection
74		Material injection
75		Painting
76		Sealing
77		Assembly
78	New Category	New Category

Figure 5.14: Task List from Concept Design – Final Product

Total product development duration was estimated and time was allocated to each activity. The overall contribution of every single group to the entire product development was determined based on the total time taken. The resulted contributions are shown in Figure 5.15.



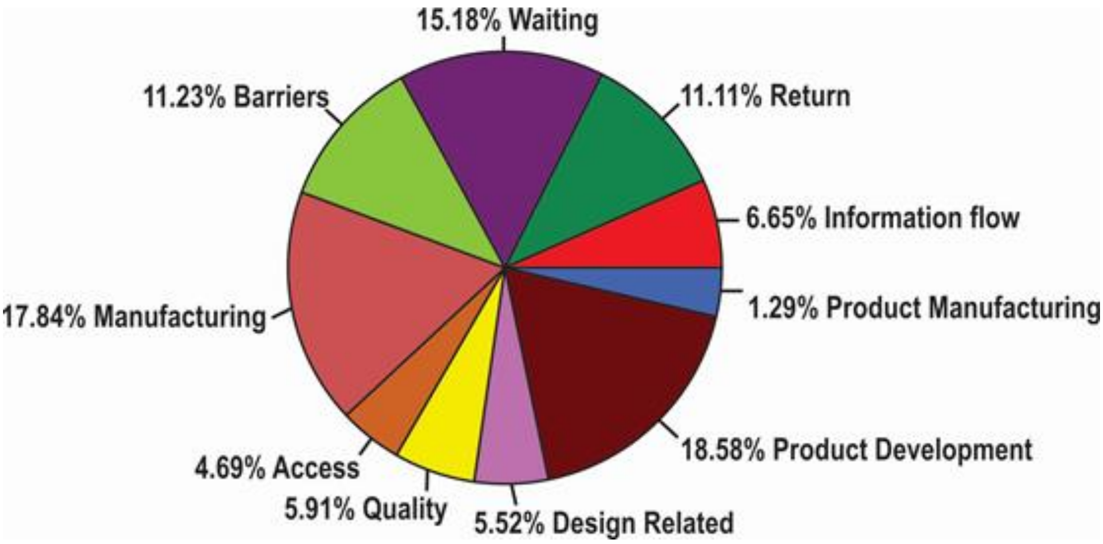


Figure 5.15: Contribution of each group in Shelter Manufacturing

It can be seen from the figures that the contribution of the product development and manufacturing was only around 36% whereas around 64% of the time was spent on other tasks like design related issues, quality, flow of information etc. From this analysis it is evident that:

i) 36% of total time spent on product development and manufacturing consisted of value added activities.

ii) The next step was to investigate that how much a proportion of the remaining 64% of time belongs to value added (VA), non-value added (NVA) or semi value added (SVA) activities?

Lengthy sessions with management were conducted to classify the activities into VA, NVA and SVA categories. The VA activities were those activities, which must be there and without that project completion is not possible. SVA were activities which were somewhat necessary but have potential to eliminate whereas NVA are activities that could be eliminated.

All 20 activities identified in Figure 5.13 were dissected on the basis of Figure 5.14, where every single activity was analysed. In other words the total time spent on the single activity was analysed to see the proportion of VA, NVA or SVA. The purpose of this activity was to determine how much contribution each activity had in the total time of the project. The results are shown in Table 5.5. The total time mentioned in Table 5.5 is in days from the concept development until the complete manufacturing of the first shelter. It also mentions the time taken by each activity VA, SVA and NVA category.

The time data in the above analysis gives an overview of how the time was utilized during the life of project. This summary was not enough to accurately determine what actually constitutes a VA, SVA or NVA category and if further advancements were required to improve the efficiency of the process, then which areas will be the candidate for improvement.

Table 5.5: Activities Distribution according to Time Consumption in each Category.

Time Study Report

ID: OTR CASE 1 — Report on: 04/02/2012 — Modified on: 03/19/2012

Time Type: Estimated — Total Time: 2556.00 Hours — Report by: STUDENT\14594474 — Modified by: STUDENT\14594474

Description: This is a case study of a fiber glass company which is extensively involved in the design, development, manufacturing and commissioning of fiber glass related products to cater the requirements of a variety of industrial sector. The particular case study focus on a specific project which was regarding the design, development, manf. And commissioning of telecom shelters for a very large Telecom company in Pakistan. The manufactured shelters were installed throughout the country. Where the telecom equipment was required to place. Very long brainstorming sessions were conducted with the General Manager Operations and Production Manager of the company as most of such activities is not documented in SMEs, which results in large amount of time, money and waste of resources. Our target was to cover the whole development process and to quantify these steps, to show that if the technology like Rapid Prototyping is there than what impact it can have on the development-prototype-manufacturing cycle.

Oper Filter: (None)

Task Summary

	ID	SEQ.	Description	Man/ Mach/Misc	Time	Ext. Time	Allow-ance	Int	Freq	VA	SVA	SVA
1)	OTR1	0.00	Generation of idea from client	Manual	72.00	72.00	0.00		1	0.00	0.00	72.00
2)	OTR2	1.00	Marketing contacted client for details	Manual	48.00	48.00	0.00		1	24.00	0.00	24.00
3)	OTR3	2.00	Visual search of already produced by others	Manual	72.00	72.00	0.00		1	24.00	12.00	36.00
4)	OTR4	3.00	Initial idea moved to GM Operations for initial screening	Manual	48.00	48.00	0.00		1	24.00	0.00	24.00
5)	OTR5	4.00	Design/Detail documentation developed	Manual	120.00	120.00	0.00		1	48.00	24.00	48.00
6)	OTR6	5.00	GM & CEO meetings and design review discussion	Manual	240.00	240.00	0.00		1	48.00	24.00	168.00
7)	OTR7	6.00	Design generation on AutoCAD	Manual	120.00	120.00	0.00		1	48.00	24.00	48.00
8)	OTR8	7.00	Design communicated to manufacturer and management	Manual	72.00	72.00	0.00		1	0.00	0.00	72.00
9)	OTR9	8.00	Financial Calculations and Manufacturing Feedback	Manual	96.00	96.00	0.00		1	24.00	0.00	72.00
10)	OTR10	9.00	Internal Review of Design	Manual	240.00	240.00	0.00		1	24.00	24.00	192.00
11)	OTR11	10.00	Material Collection from open market for prototyping	Manual	144.00	144.00	0.00		1	0.00	0.00	144.00
12)	OTR12	11.00	Equipment requirement and development for prototyping	Manual	240.00	240.00	0.00		1	24.00	24.00	192.00
13)	OTR13	12.00	First prototype development	Manual	144.00	144.00	0.00		1	24.00	0.00	120.00
14)	OTR14	13.00	Clients Arrival and proposed changes	Manual	120.00	120.00	0.00		1	50.00	20.00	50.00
15)	OTR15	14.00	Verification by client	Manual	144.00	144.00	0.00		1	5.00	20.00	119.00
16)	OTR16	15.00	Verification by CEO	Manual	48.00	48.00	0.00		1	24.00	0.00	24.00
17)	OTR17	16.00	Design Changes once Manufacturing Started	Manual	84.00	84.00	0.00		1	0.00	0.00	84.00
18)	OTR18	17.00	Cam Lock Design issue	Manual	96.00	96.00	0.00		1	24.00	0.00	72.00
19)	OTR19	18.00	Fault detected due to conventional manufacturing system	Manual	48.00	48.00	0.00		1	24.00	24.00	0.00
20)	OTR20	19.00	R&D Demand for polyurethane injection	Manual	360.00	360.00	0.00		1	120.00	96.00	144.00

A novel approach was employed to further analyse the project activities and to observe what went on during the life of the project. This approach used the flow planner module of the proplanner software, which is basically used to draw the material flow diagram in an AutoCAD environment.

An existing module of the proplanner was modified in AutoCAD so it resembled the original company A layout. The layout was drawn to scale based on the approximate distances between offices, from head office to factory and between manufacturing processes to get more accurate results.

The first step was to identify the activity to analyse the type of information flow and to document the transfer that occurred from which place to what location. Figure 5.16 shows the information routing of the complete project.

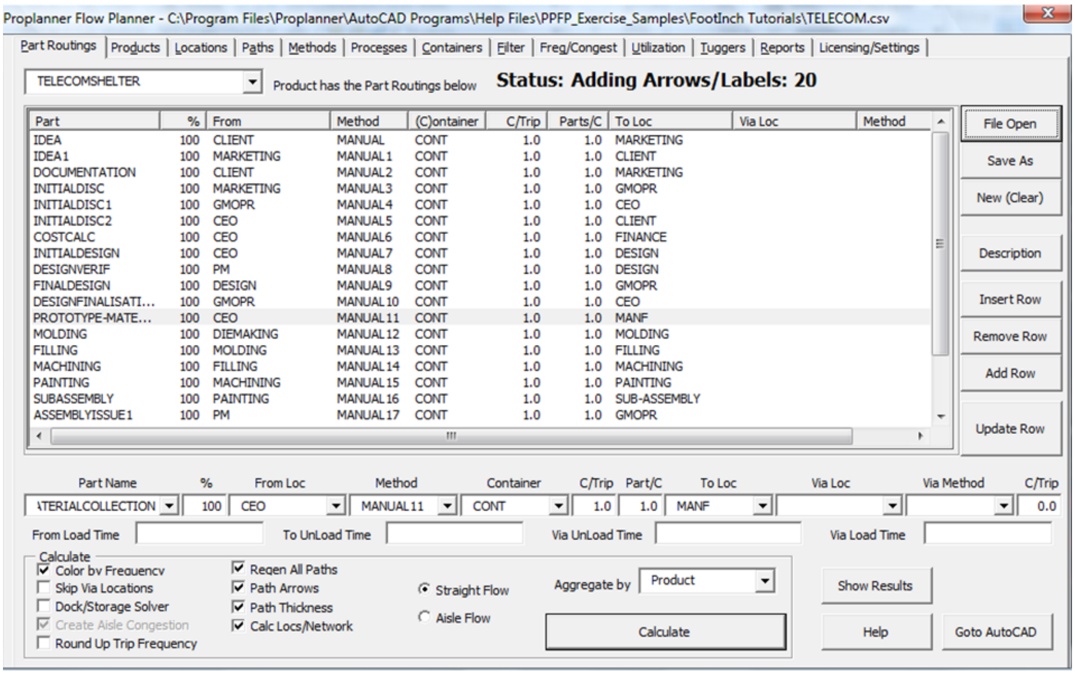


Figure 5.16: Information Routing for Telecom Shelter

A total of 21 activities were identified along with their direction of flow. As an example, the first activity was the IDEA which flows from the CLIENT to MARKETING as shown in Figure 5.16. It also incorporated the manufacturing process routing which was actual material flow.

The second step was to identify the quantity of each activity and the numbers of days that were approximately spent on each task. As this analysis deals with information flow it also considered “how many times the event occurred”. For example, the initial design was reviewed 40 times as shown in Figure 5.17. This means that the initial design was moved 40 times between departments for consensus and finalization. Different colours were allocated to differentiate between activities. A complete list of frequency of activities is shown in Figure 5.17.

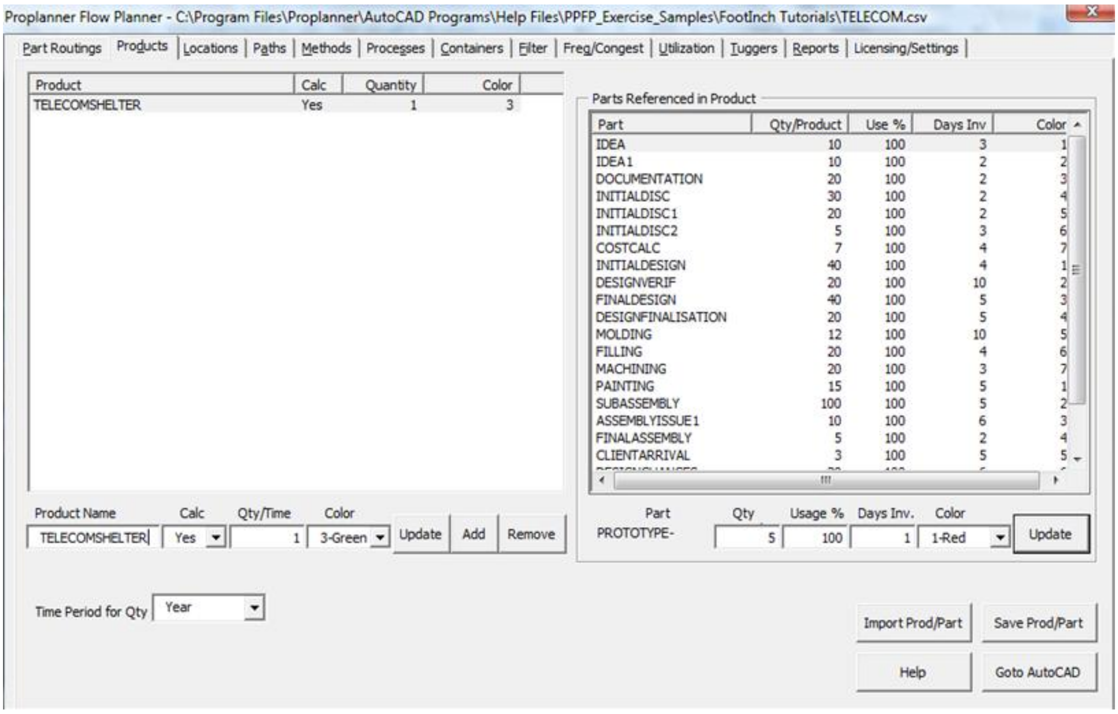


Figure 5.17: Frequency of Activities and Duration

Activities were grouped together in the third step. Locations were identified through X and Y coordinates of each activity/location. These coordinates were used to determine the distance travelled from one location to another location. A complete list of locations of all the functions is given in Figure 5.18.

One of the critical tasks was to determine the cost of each activity based on the time taken, the frequency and the type of activity. For example consider the flow of information between the Production and General Manager. This cost will be entirely different than that between the marketing and finance section due to the difference in wages.

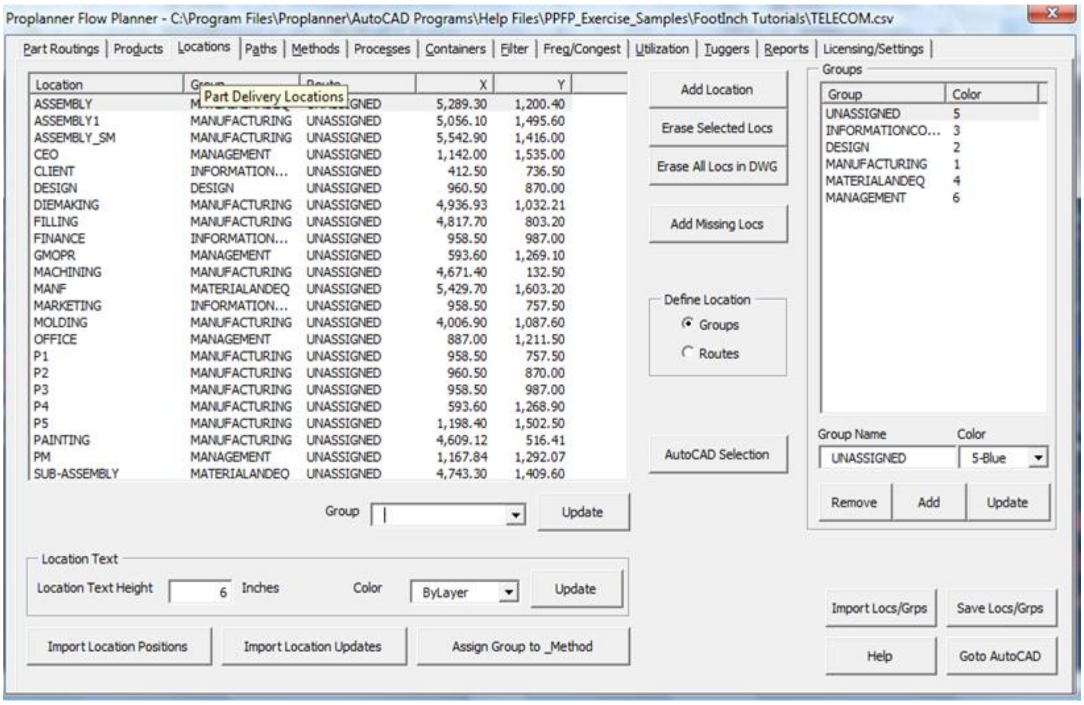


Figure 5.18: Location Determination of each Function

Without this step it was not possible to estimate how much cost each activity would carry? The other advantages of activity costing were:

i) Determine and document the cost of each operation, for the sake of improvement and to determine the role of any new intervention.

ii) Demonstrate the importance and effectiveness of the lean operations; otherwise activities at this smaller scale were normally ignored due to the incorrect assumption that they have minimal impact on the total cost of the project.

Cost parameters were developed based on the type of activity, nature of involvement and who or what is involved. Figure 5.19 gives a snapshot of the costing process.

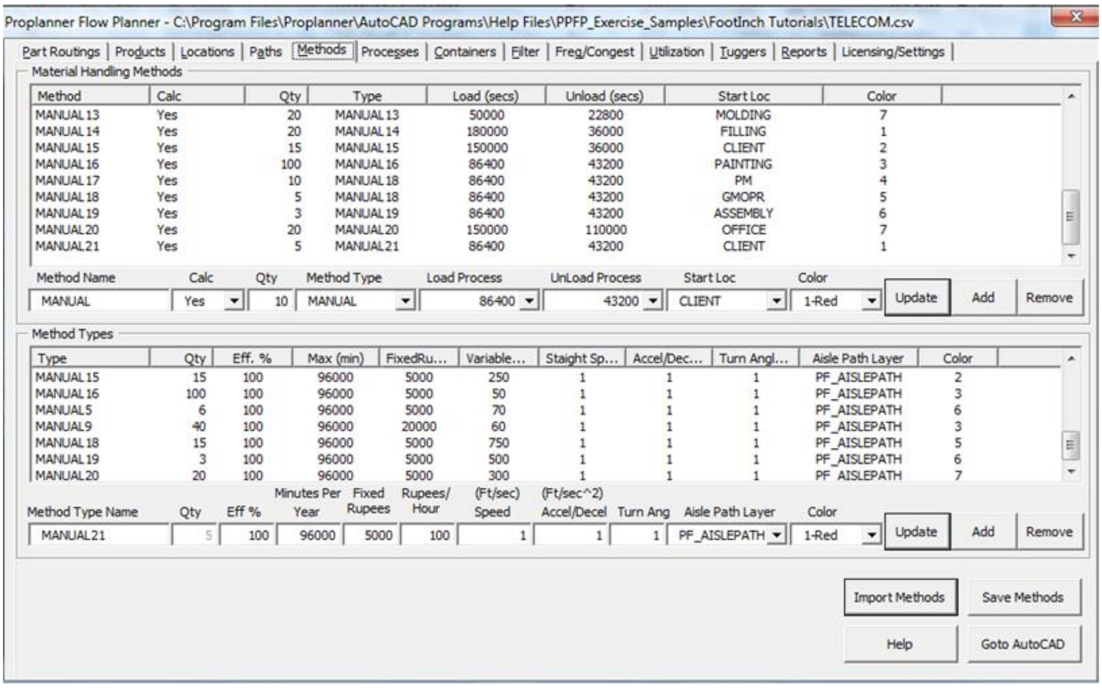


Figure 5.19: Activities Costing Process

A layout of the business was redesigned using an existing Proplanner Flow Analysis template. The layout approximately represents the distance on scale from one location to another and is shown in Figure 5.20.

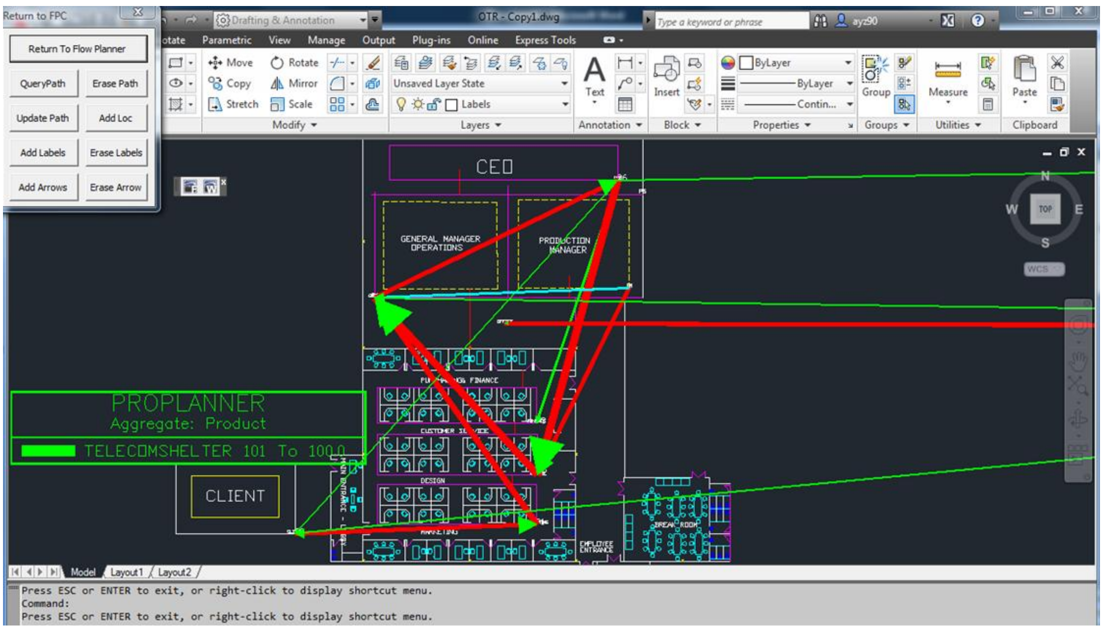


Figure 5.20: Information/Material Flow during Planning Phase

The flow of information during the product development process is represented by lines and arrows. The thickness of the line represents the number of times the information flows between two persons/departments. It is also evident that a significant amount of time was spent during the development stage on discussion and meetings between management. This again required design modification and new channels of information was required. Figure 5.21 shows the flow of information/ material between design and manufacturing, as manufacturing was located at a distance of 30 kilometres from the design office. It also shows the frequency of activities within the manufacturing facility.

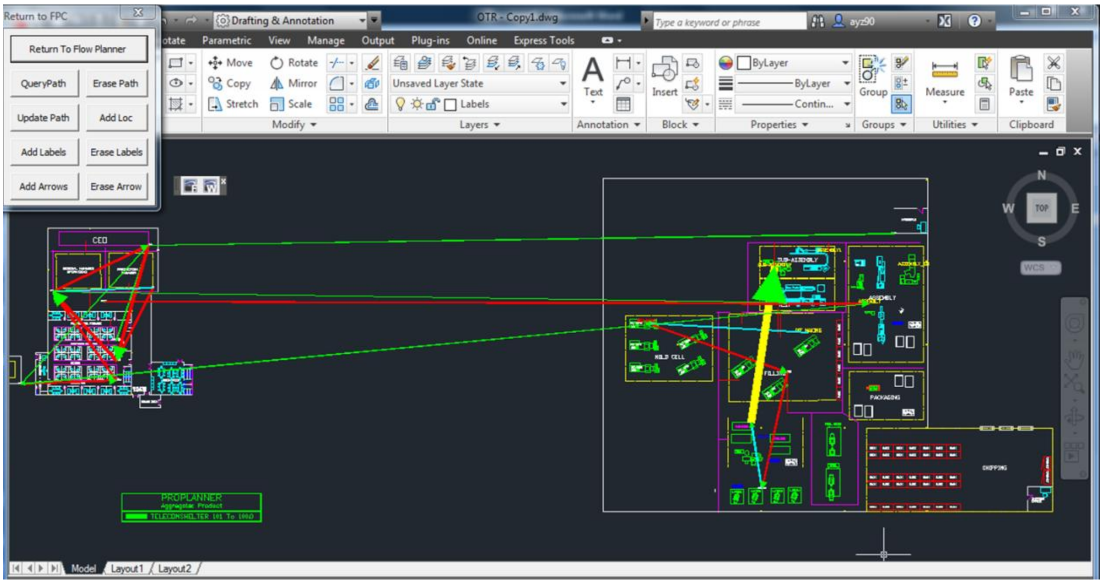


Figure 5.21: Detailed Flow Analysis of Shelter Development

The thickness of lines gives indication of how much repetition of information was involved due to constant changes in the design. The analysis can be used as a reference where any future initiatives for lean product development and its impact can be quantified.

The next section provides details regarding the development and application of the Decision Support System to determine an optimal prototyping process for a given application.

5.5 COMPARE/Technology Selection

The purpose of this step was to provide assistance in the selection of the right RP technology based on the user company requirements. A Decision Support System (DSS) based on AHP was developed to select the right technology from tens of available options. The development of a DSS involved several steps. These included;

1) Clear definition of the problem and its scope.

2) Critical selection and data collection criteria.

3) Information document creation and coding.

4) Selection of the system capable of solving the defined problem and its application related issues. Collection of the data for alternatives against the defined selection criteria and finally refinements in the model to make it ready for applications.

5.5.1 Problem Definition/Important Considerations

The important considerations for an effective development of DSS were:

i) It must include factors, which are critical for the selection of the right technology but at the same time should be easily understandable by the company or individual user.

ii) Capable of considering both qualitative and quantitative factors, to arrive at a better decision.

iii) As most of the SMEs are still reliant on CNC (subtractive) processes and in some cases it provides better results than RP so it must be able to inform when added or subtractive processes is required.

iv) In some cases, RP equipment purchase is not a feasible option, so it should guide for any "make or buy" related decisions. In other words when to use a service bureau option.

v) The developed DSS should be able not only to select a system but also provide a complete guide on the process and equipment.

vi) DSS should find its application for both SMEs and large corporations.

vii) Generate a list of selected equipment and rank them based on the user requirements.

5.5.2 Selection of the Criteria and Data Collection

The main objective of this step was to identify the criteria which must be considered during any RP technology acquisition process. The identified criteria for the selection of a suitable technology was grouped into four main groups named material choice, product profile, process potential and process economy. Material choice includes around 45 types of materials clustered into 12 groups for ease of computation.

Product profile criteria provide selection on the basis of complexity, feature details and application. The selection is based on the profile of the selected product like complex curves or small parts and its intended use and matches these preferences with the available technologies.

Process potential criteria include the desired surface finish and build accuracy. It also gives an option of build time and build size preference as all the RP equipment vary in size and speed due to the type of prototyping processes employed in the RP equipment.

Process economy consists of many factors which include volume of product required, lead time importance, type of work and critical cost factor which includes equipment material, labour and maintenance cost. A complete selection model has already been shown in Figure 4.4.

The data was collected for more than 80 commercially available RP systems worldwide. The data was grouped into two categories named qualitative and quantitative according to the selection criteria. Figure 5.22 shows the build size comparison data whereas Figure 5.23 shows surface finish and accuracy data used for the DSS knowledge base. Both figures show large variation in the capabilities of the available RP equipment.

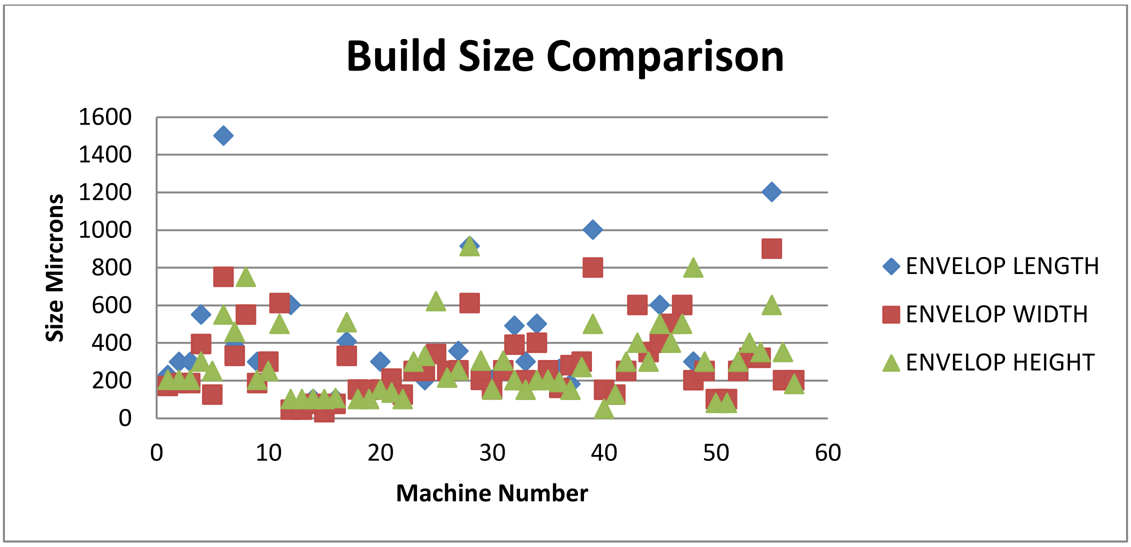


Figure 5.22: Build Size Comparison Data

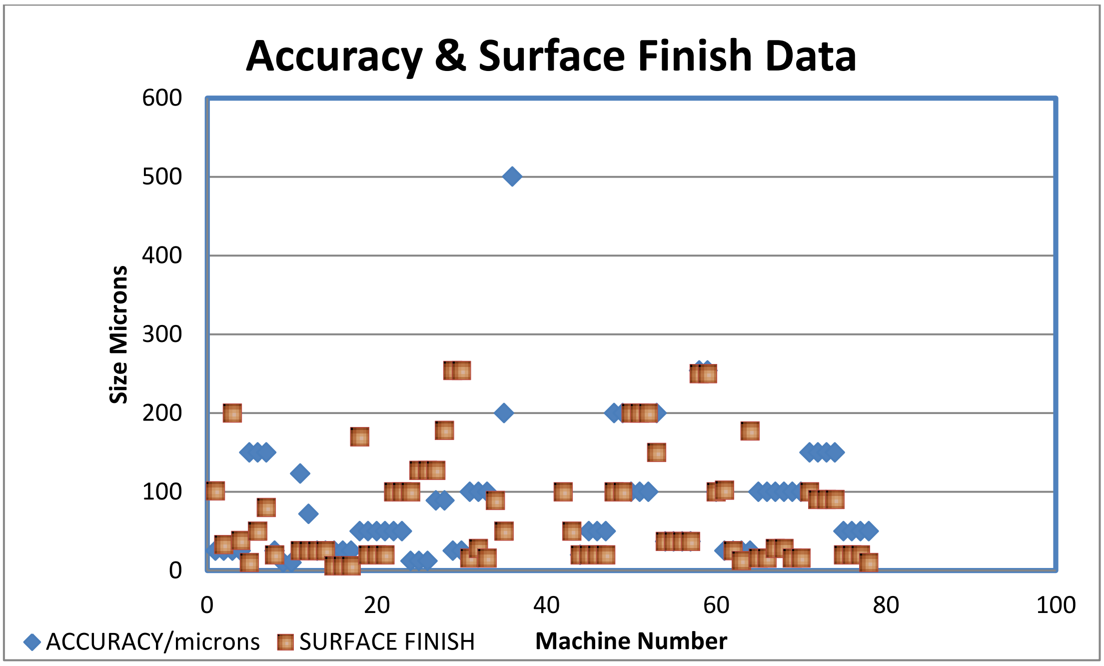


Figure 5.23: Surface Finish and Accuracy Data

5.5.3 Decision Support System Information Document and Coding

The DSS was designed in a way that it does not select equipment only but it also provides the basic information about the Rapid Prototyping and Additive Manufacturing Process as shown in Figure 5.24.

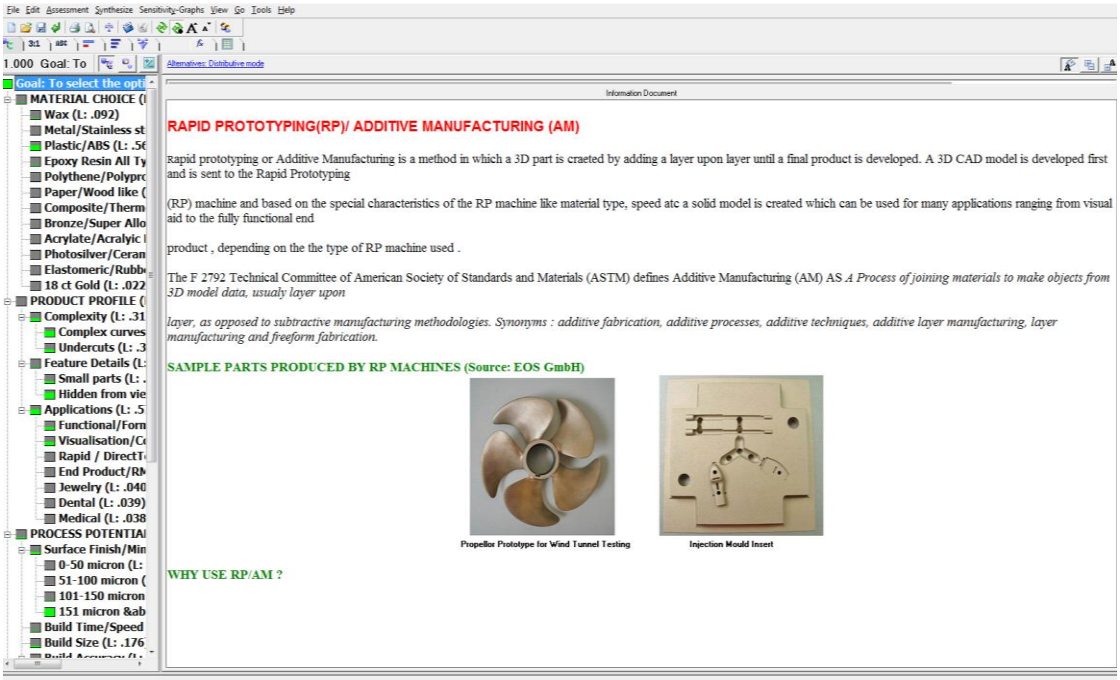


Figure 5.24: Information Document to Explain the RP Process

The second step was to provide a complete listing of the detail of all the selected equipment. Figure 5.25 shows the technical information of the selected equipment which ranges from all the technical specifications to the contact details.

Once the hierarchy and information documents were created, the next step was to create the knowledge base (called Data Grid in Expert Choice) of the system. Since there were more than 80 alternatives it was extremely difficult to rank them against the tens of selection criterion, especially for those who are novices to the RP technology. This issue required the development of a fixed database which did not require user intervention.

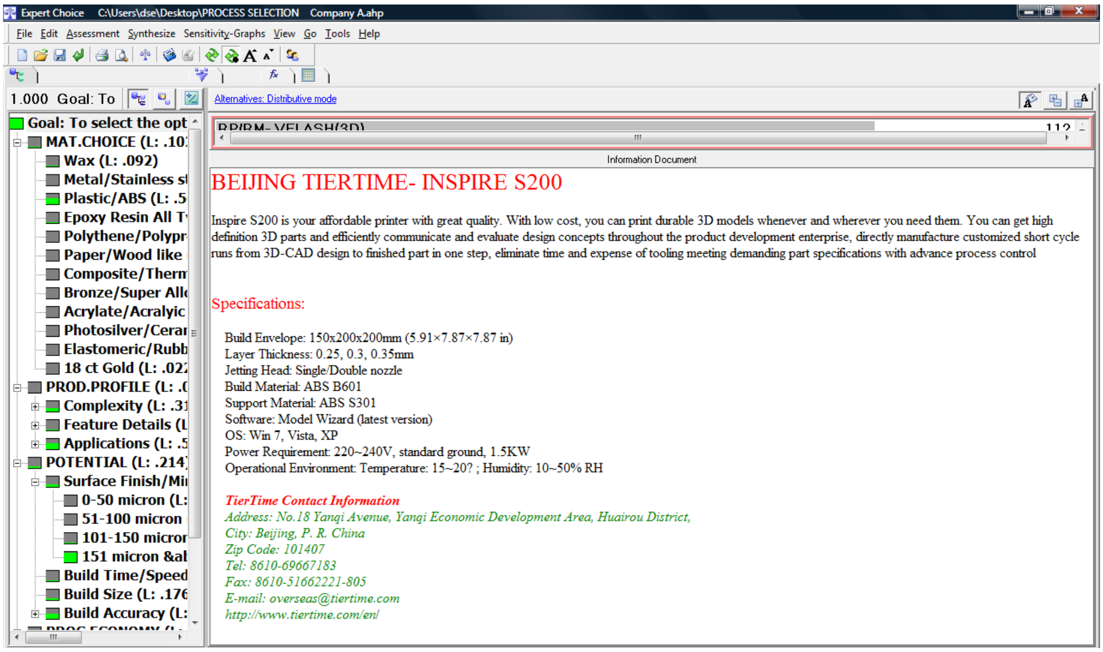


Figure 5.25: Information Document for Equipment Detail

Two different types of coding were used to handle both the qualitative and quantitative data inputs. The first method called Rating Formula approach was used for cases where no hard data was available and subjective evaluations were required. The priorities were derived for ratings and evaluation of each alternative against every single alternative was performed based on the available information.

The second approach called Step Function, consists of scaling of the prioritized intensities but the main difference between the rating and step approaches is that the step function automatically calculates the required intensity based on the data entered in the Data Grid. Figure 5.26 shows an overview of the Rating Step formulas of few of the alternatives developed for the DSS.

Covering Objectives / Formulas	Type	Low / I1	High / I2	Curve / I3	I4	I5	I6	I7	I8	I9	I10
MATERIAL CHOICE \ Wax	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Metal/Stainless	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Plastic/ABS	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Epoxy Resin All	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Polythene/Polyr	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Paper/Wood lik	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Composite/Ther	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Bronze/Super A	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Acrylate/Acralyi	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Photosilver/Cer	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ Elastomeric/Rul	RATINGS	Yes	Partial witl	No							
MATERIAL CHOICE \ 18 ct Gold	RATINGS	Yes	Partial witl	No							
PRODUCT PROFILE \ Complexity \ C	STEP	Excellent|1	Very Gooc	Good|2	Average|3						
PRODUCT PROFILE \ Complexity \ U	STEP	Excellent|1	Very Gooc	Good|2	Average|3						
PRODUCT PROFILE \ Feature Details	STEP	Excellent|1	Very Gooc	Good|2	Average|3						
PRODUCT PROFILE \ Feature Details	STEP	Excellent|1	Very Gooc	Good|2	Average|3						
PRODUCT PROFILE \ Applications \	RATINGS	Excellent	Very Gooc	Good	Fair	Poor					
PRODUCT PROFILE \ Applications \	RATINGS	Excellent	Very Gooc	Good	Fair	Poor					
PRODUCT PROFILE \ Applications \	RATINGS	Excellent	Very Gooc	Good	Fair	Poor					
PRODUCT PROFILE \ Applications \	RATINGS	Excellent	Very Gooc	Good	Fair	Poor					
PRODUCT PROFILE \ Applications \	RATINGS	Yes	No	Partial							
PRODUCT PROFILE \ Applications \	RATINGS	Yes	No	Partial							
PRODUCT PROFILE \ Applications \	RATINGS	Yes	No	Partial							
PROCESS POTENTIAL \ Surface Fini	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS POTENTIAL \ Surface Fini	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS POTENTIAL \ Surface Fini	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS POTENTIAL \ Surface Fini	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS POTENTIAL \ Build Time/S	RATINGS	Fast	Medium	Slow							
PROCESS POTENTIAL \ Build Size	STEP	Very Low|0	Low|15	Medium|2	High|45	Very High|					
PROCESS POTENTIAL \ Build Accure	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS POTENTIAL \ Build Accure	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS POTENTIAL \ Build Accure	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS POTENTIAL \ Build Accure	RATINGS	Ideal	Ok to use	Not Suitab							
PROCESS ECONOMY \ Production Vc	RATINGS	Good	Not Suitab								
PROCE[illegible]	[illegible]GS	Good	Not Suitab								
PROCESS ECONOMY \ Lead Time	RATINGS	High	Low								
PROCESS ECONOMY \ Work type \ F	RATINGS	Ideal	Not Suitab								
PROCESS ECONOMY \ Work type \ (	RATINGS	Ideal	Not Suitab								
PROCESS ECONOMY \ Cost \ Equipr	STEP	Very Cheap	Cheap|15(	Average|3	Moderate|	Expensive	Very Expe				
PROCESS ECONOMY \ Cost \ Materi	STEP	Very Low|0	Low|15	Medium|8(	High|300	Very High|					
PROCESS ECONOMY \ Cost \ Mainte	STEP	Very Low|0	Low|3000	Medium|5(	High|1500	Very High|					
PROCESS ECONOMY \ Cost \ Labor	RATINGS	Easy	Relatively	Minimal SI	Skilled	Highly Ski					

Type column is only editable column on this grid

Figure 5.26: Formula Grid

Once the Rating Formulas were developed, data of each alternative against the selected criterion were entered into the Data Grid to generate a complete knowledge base.

The DSS was tested several times by considering the potential scenarios, to manually confirm that it was able to deliver the desired results. Several adjustments were made in defining formulas to ensure that it arrived at the best results before the system was utilised for real time application in the targeted companies.

5.5.4 Application of the Process Selection Decision Support System

The Decision Support System was used in both companies A and B to select the optimal process based on the user company requirement. The Telecom Shelter shown in Figure 5.1 was considered as the candidate for process selection. A few of the requirements of the company were;

Material:	ABS plastic or wax or epoxy resins
Surface Finish:	150µm
Accuracy:	55µm
Production Description:	Complex, undercuts
Production Volume:	1-100/month
Application:	Visualisation, Form Fit
Material Cost:	Cheapest Possible
Equipment Cost:	Cheap

The above requirements contain both the qualitative and qualitative input. It is impossible that all the selection criteria to carry equal weightage for one company to another due to the difference in user's requirements. To determine the importance of one element to one at the upper level, the following priority vectors were used (Armillotta, 2008) "

$$a = [a_i, i = 1 \dots \dots \dots n_A] \tag{5.2}$$

$$b^i = \left[b_j^{(i)}, j = 1 \dots \dots \dots n_B\right], i = 1, \dots \dots n_A, \tag{5.3}$$

$$c^{(j)} = \left[c_k^{(j)}, k = 1 \dots \dots \dots n_C\right], j = 1, \dots \dots n_B, \tag{5.4}$$

where,

i) n_A, n_B, n_C are the number of criteria categories (n_A = 4), attributes (n_B = 49) and alternatives (n_B = 82) considered in the DSS

ii) $a_i \in \{0,1\}$ is the relevance of the i^{th} criteria to the application

iii) $b_j^i \in \{0,1\}$ is the priority of the j^{th}attribute with the i^{th}criteria

iv) $c_k^{(j)} \in \{0,1\}$ k^{th}alternative priority with respect to the j^{th}attribute".

Priority vector P can be obtained as,

$$P_k = \sum_{i=1}^{nA} \left(a_i \sum_{j=1}^{nB} b_j^{(i)} \, c_k^{(i)} \right), k = 1 \ldots . n_c, \tag{5.5}$$

Expert choice was used to perform these computations to determine the overall priority.

The practitioners were asked to perform pairwise comparison, to prioritise the four main criteria. A sample pairwise comparison process is shown in Figure 5.27.

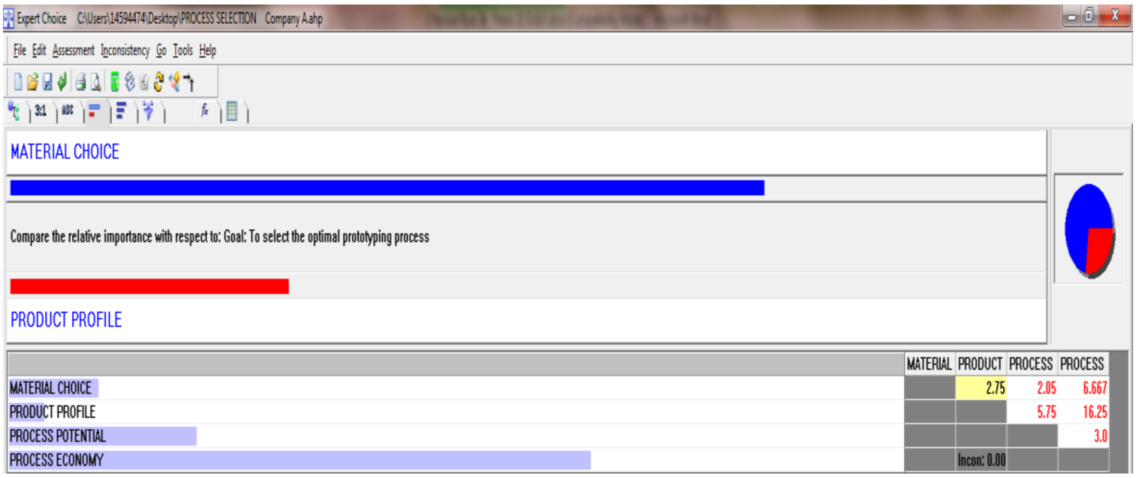


Figure 5.27: Pairwise Comparison of Material Choice & Product Profile

The resultant priorities are shown in Figure 5.28.

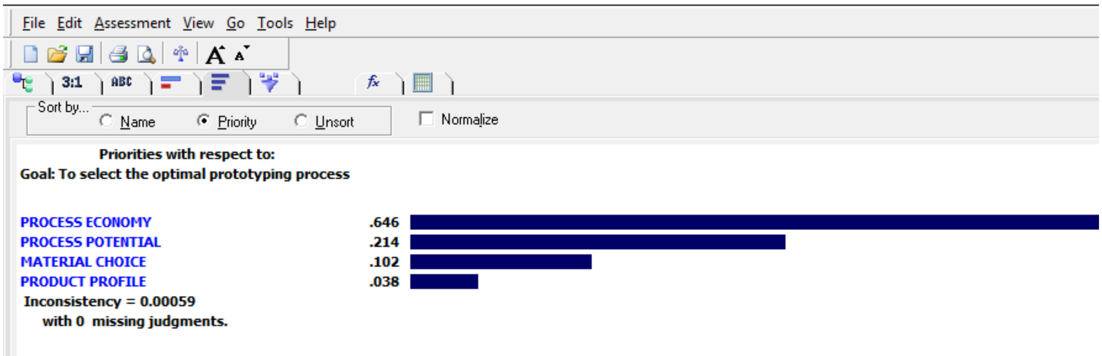


Figure 5.28: Priorities of Main Objectives with respect to Goal

The normalized priorities are shown in Figure 5.29.

Figure 5.29: Normalized Priorities

It is evident in Figures 5.28 and 5.29 that process economy emerged as the most important factor followed by the process potential.

The next step was the determination of the priority value for the material mentioned under the category of Material Choice. Figure 5.30 shows the questionnaire used to determine the material priority and the values obtained.

Compare the relative importance with respect to: MATERIAL CHOICE (L: .102)

Circle one number per row below using the scale:
1 = Equal 3 = Moderate 5 = Strong 7 = Very strong 9 = Extreme

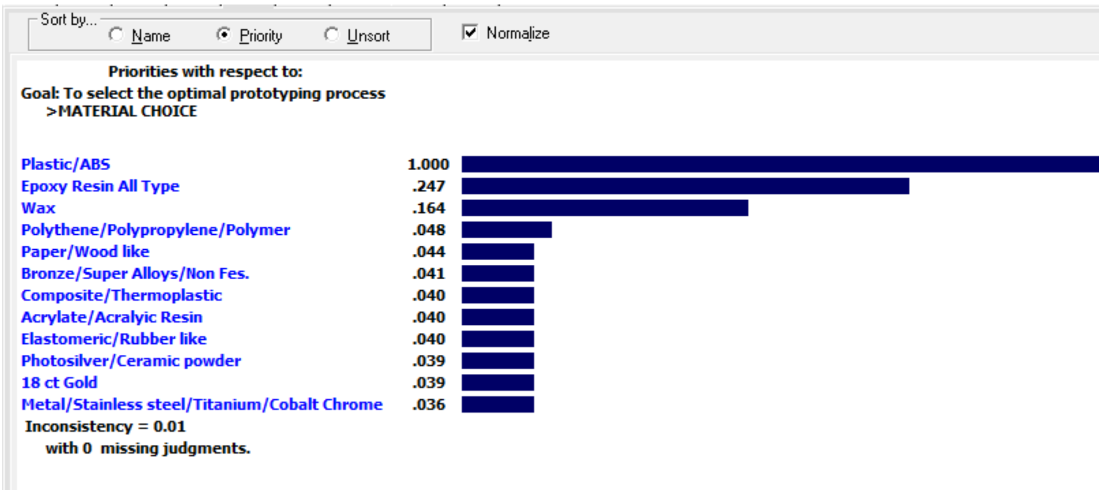
1	Wax	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Metal/Stainless steel,
2	Wax	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Plastic/ABS
3	Wax	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Epoxy Resin All Type
4	Wax	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Polythene/Polypropyl
5	Wax	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Paper/Wood like
6	Wax	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Composite/Thermopl
7	Wax	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Bronze/Super Alloys/
8	Wax	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Acrylate/Acralyic Res
9	Wax	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Photosilver/Ceramic
10	Wax	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Elastomeric/Rubber l
11	Wax	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	18 ct Gold
12	Metal/Stainless steel,	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Plastic/ABS
13	Metal/Stainless steel,	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	Epoxy Resin All Type
14	Metal/Stainless steel,	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Polythene/Polypropyl
15	Metal/Stainless steel,	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Paper/Wood like
16	Metal/Stainless steel,	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Composite/Thermopl
17	Metal/Stainless steel,	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Bronze/Super Alloys/
18	Metal/Stainless steel,	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Acrylate/Acralyic Res
19	Metal/Stainless steel,	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Photosilver/Ceramic
20	Metal/Stainless steel,	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Elastomeric/Rubber l
21	Metal/Stainless steel,	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	18 ct Gold
22	Plastic/ABS	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Epoxy Resin All Type
23	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Polythene/Polypropyl
24	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Paper/Wood like
25	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Composite/Thermopl
26	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Bronze/Super Alloys/
27	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Acrylate/Acralyic Res
28	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Photosilver/Ceramic
29	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elastomeric/Rubber l
30	Plastic/ABS	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	18 ct Gold
31	Epoxy Resin All Type	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Polythene/Polypropyl
32	Epoxy Resin All Type	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Paper/Wood like
33	Epoxy Resin All Type	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Composite/Thermopl
34	Epoxy Resin All Type	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Bronze/Super Alloys/
35	Epoxy Resin All Type	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Acrylate/Acralyic Res
36	Epoxy Resin All Type	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Photosilver/Ceramic
37	Epoxy Resin All Type	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Elastomeric/Rubber l
38	Epoxy Resin All Type	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	18 ct Gold
39	Polythene/Polypropyl	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Paper/Wood like
40	Polythene/Polypropyl	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Composite/Thermopl
41	Polythene/Polypropyl	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Bronze/Super Alloys/
42	Polythene/Polypropyl	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Acrylate/Acralyic Res
43	Polythene/Polypropyl	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Photosilver/Ceramic
44	Polythene/Polypropyl	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Elastomeric/Rubber l
45	Polythene/Polypropyl	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	18 ct Gold
46	Paper/Wood like	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Composite/Thermopl
47	Paper/Wood like	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Bronze/Super Alloys/
48	Paper/Wood like	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Acrylate/Acralyic Res

Figure 5.30: Pairwise Comparison of the Material Choice

As the preferred material for Company A was ABS plastic, so the user can create a list of preferred materials, by providing preference of one material over the other. A nine point rating scale shown in Figure 5.30 was employed. Once all the ratings have been completed, a complete list of priorities of each material was obtained which is shown in Table 5.5.

Table 5.6: Assessment of Material Priorities with respect to Main Objective Material Choice.

Materials	Wax	Met	Pl	EP	POL	PAP	COMP	Br	ACR	PH	EL	GO
Wax	1	5.81	5.31	3.7	2.58	4.28	4.72	4.39	4.14	4.12	4.21	5.06
Met	X	1	30.92	7.28	1.8	1.15	1.12	1.09	1.03	1.04	1.1	1.11
Pl	X	X	1	3.96	18.39	18.15	30.92	29.04	24.11	29.64	28.46	21.87
EP	X	X	X	1	4.01	4.61	6.16	4.3	5.96	5.66	3.96	5.28
POL	X	X	X	X	1	1.09	1.02	1.03	1.06	1.05	1.07	1.05
PAP	X	X	X	X	X	1	1.05	1.02	1.07	1.05	1.1	1.14
COMP	X	X	X	X	X	X	1	1.06	1.04	1.04	1.07	1.03
Br	X	X	X	X	X	X	X	1	1.03	1.1	1.01	1.08
ACR	X	X	X	X	X	X	X	X	1	1.15	1.03	1.02
PH	X	X	X	X	X	X	X	X	X	1	1.04	1.06
EL	X	X	X	X	X	X	X	X	X	X	X	1.05
GO	X	X	X	X	X	X	X	X	X	X	X	X

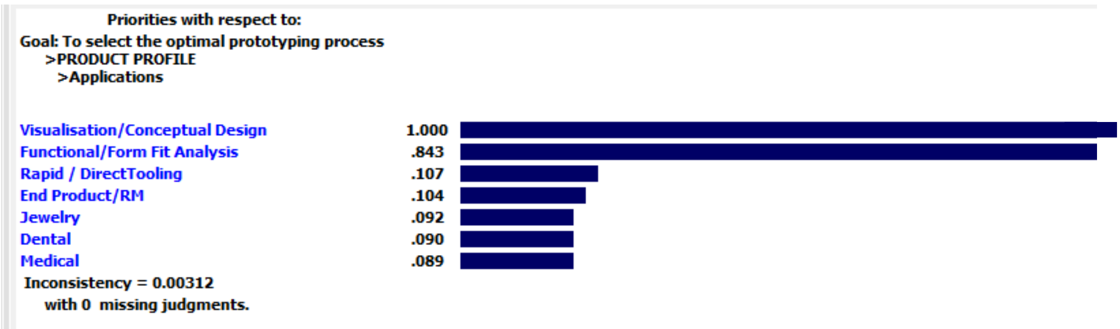


It is shown in Table 5.5 that Plastic/ABS has received the first preference whereas Resins and Wax received the second and third places in a complete priority list for material selection. The overall inconsistency was 0.01, which is well below the permitted 0.1 limit and shows that the comparison was consistent.

The pairwise comparison continued to the lower level. Another comparison for the "Applications" module of the selection criterion is shown in Table 5.6.

Table 5.7: Pairwise Comparison Results of Application Criteria

	Funct.	Vis.	Rpd.	End Pr.	Jew.	Den.	Med.
Funct.	1	1.15	5.84	8.4	10.78	9.79	9.42
Vis.	X	1	9.2	9.2	11.5	11.5	11.5
Rpd.	X	X	1	1.12	1.04	1.13	1.14
End Pr.	X	X	X	1	1.08	1.15	1.1
Jew.	X	X	X	X	X	1.05	1.07
Den	X	X	X	X	X	X	1.06
Med.	X	X	X	X	X	X	X



The table clearly indicates that the main "Application" preference of Company A was Visualisation/Concept Design whereas the second preference was Form Fit Analysis, which is consistent with the company's requirements defined initially.

The pairwise process continued for every single criterion mentioned in the hierarchy to obtain the previous ratings. A complete synthesis of priorities with calculated rating values is shown in Table 5.7. The DSS synthesize the ratings results against all the alternatives and their ratings were stored in the Data Grid to compute a list of selected equipment based on their computed rating.

Table 5.8: Computed Priorities for Selection Criteria

(Main Criteria)	Sub Criteria	Priority	Sub-Sub Criteria
Material Choice (0.102)	Wax	0.092	
	Metal	0.020	
	Plastic	0.562	
	Epoxy	0.139	
	Polythane	0.027	
	Paper	0.025	
	Compos.	0.022	
	Bronze	0.023	
	Acryl	0.022	
	Photo Silver	0.022	
	Elastomeric	0.023	
	Gold	0.022	
Product Profile (0.038)	Complexity	0.316	
		0.655	Complex Curves
		0.345	Undercuts
	Feature Details	0.107	
		0.244	Small Parts
		0.756	Hidden From Views
	Applications	0.577	
		0.363	Functional
		0.430	Visualisation
		0.046	Rapid Tooling
		0.045	End Product
		0.040	Jewellery
		0.039	Dental
		0.038	Medical
Process Potential (0.214)	Surface Finish	0.237	
		0.008	0-50 micron
		0.008	51-100 micron
		0.116	101-150 micron
		0.868	151 micron & above
	Build Time	0.067	
	Build Size	0.176	
	Build Accuracy	0.519	
		0.009	0-25 micron
		0.011	26-50 micron
		0.049	51-100 micron
		0.931	101 micron & above
Process Economy (0.646)	Production Volume	0.074	
		0.872	Low
		0.128	High
	Lead Time	0.359	
	Work Type	0.101	
		0.980	Regular
		0.020	Occasional
	Cost	0.465	
		0.713	Eq. Cost
		0.176	Mat. Cost
		0.105	Maint. Cost
		0.006	Lab. Cost

Appendix H gives an overview of the data grid. The computed list of equipment that satisfies the company A requirement is shown in Figure 5.31.

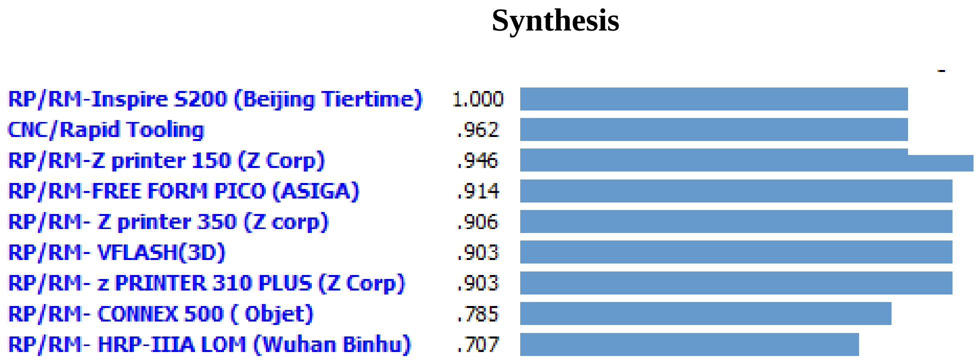


Figure 5.31: Recommended List of Equipment & Ranking (Highly Recommended on Top)

A list of the 9 recommended products is shown in Figure 5.31. This list is based on the rating of each alternative against each element and based on the ranking of the selection criteria. Originally a list of all alternatives was created but only 9 alternatives based on the ranked value from high to low were selected. This was recommended by Expert Choice to ease the analysis process. The list clearly indicates that CNC (subtractive) process cannot be eliminated and is good for certain operations desired by Company A. The list was manually verified for all the costing and material properties in the database and was found to be the best equipment able to cater for the requirements of the user Company A.

For Company B, two products named Air cooled Engine Cylinder and Fluid Tank were nominated for the selection of the optimal process. Some important requirements of the company were:

i) Material Preference: 1. Metal 2. Plastic

ii) Accuracy Requirements: More than 101µm

iii) Surface Finish: More than 150µm

iv) Build Size: Large

v) Lead Time: High Importance

vi) Product Profile: The product contains complex curves but does not contain small features.

vii) Application: Functional/Form Fit Analysis : Visualisation

viii) Production Volume Requirements: Low

The company was currently using service Bureau for Rapid Prototyping.

Pairwise comparison was done by the Company B managers and the resulting priority values obtained for all main and sub criteria are shown in Figure 5.32.

Model Name: Company B PROCESS SELECTION

Treeview

- **Goal: To select the optimal prototyping process**
  - **MATERIAL CHOICE (L: .333)**
    - **Wax (L: .005)**
    - **Metal/Stainless steel/Titanium/Cobalt Chrome (L: .609)**
    - **Plastic/ABS (L: .347)**
    - **Epoxy Resin All Type (L: .004)**
    - **Polythene/Polypropylene/Polymer (L: .004)**
    - **Paper/Wood like (L: .004)**
    - **Composite/Thermoplastic (L: .004)**
    - **Bronze/Super Alloys/Non Fes. (L: .004)**
    - **Acrylate/Acralyic Resin (L: .004)**
    - **Photosilver/Ceramic powder (L: .004)**
    - **Elastomeric/Rubber like (L: .004)**
    - **18 ct Gold (L: .004)**
  - **PRODUCT PROFILE (L: .134)**
    - **Complexity (L: .280)**
      - **Complex curves (L: .507)**
      - **Undercuts (L: .493)**
    - **Feature Details (L: .107)**
      - **Small parts (L: .444)**
      - **Hidden from view (L: .556)**
    - **Applications (L: .613)**
      - **Functional/Form Fit Analysis (L: .431)**
      - **Visualisation/Conceptual Design (L: .295)**
      - **Rapid / DirectTooling (L: .061)**
      - **End Product/RM (L: .054)**
      - **Jewelry (L: .050)**
      - **Dental (L: .057)**
      - **Medical (L: .053)**
  - **PROCESS POTENTIAL (L: .077)**
    - **Surface Finish/Minimum Layer Thickness (L: .066)**
      - **0-50 micron (L: .104)**
      - **51-100 micron (L: .098)**
      - **101-150 micron (L: .144)**
      - **151 micron &above (L: .655)**
    - **Build Time/Speed (L: .028)**
    - **Build Size (L: .796)**
    - **Build Accuracy (L: .110)**
      - **0-25 micron (L: .079)**
      - **26-50 micron (L: .091)**
      - **51-100 micron (L: .108)**
      - **101 micron &above (L: .722)**
  - **PROCESS ECONOMY (L: .456)**
    - **Production Volume (L: .013)**
      - **Low (1-100 or 1000/year) (L: .897)**
      - **High/ more than 1000 (L: .103)**
    - **Lead Time (L: .154)**
    - **Work type (L: .026)**
      - **Regular (L: .028)**
      - **Occassional (L: .972)**
    - **Cost (L: .806)**
      - **Equipment cost (L: .402)**
      - **Material cost (L: .290)**
      - **Maintenance cost (L: .199)**
      - **Labor cost/Skilled labor (L: .109)**

Figure 5.32: Priority Values of Company B Process Selection

Process Economy was number one preference followed by the material choice as shown in Figure 5.32. The computed normalized list of the resulting recommended RP equipment is shown in Figure 5.33.

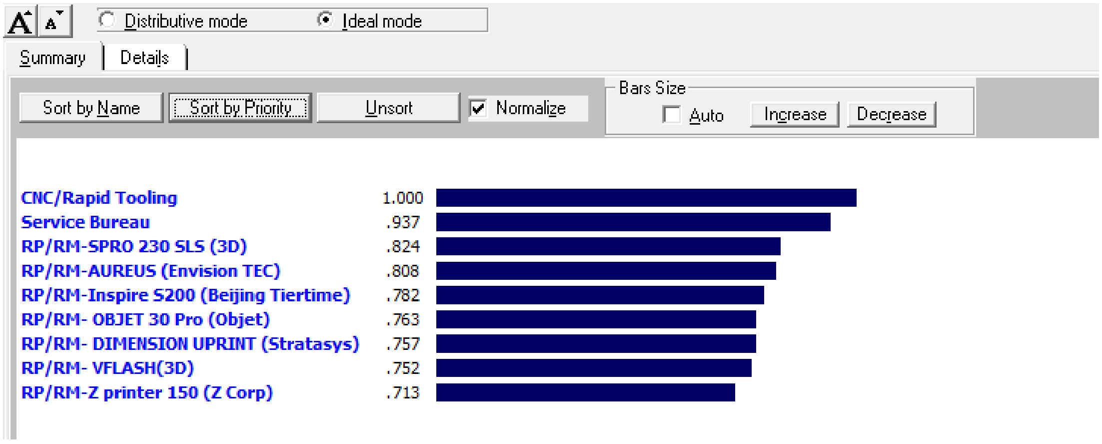
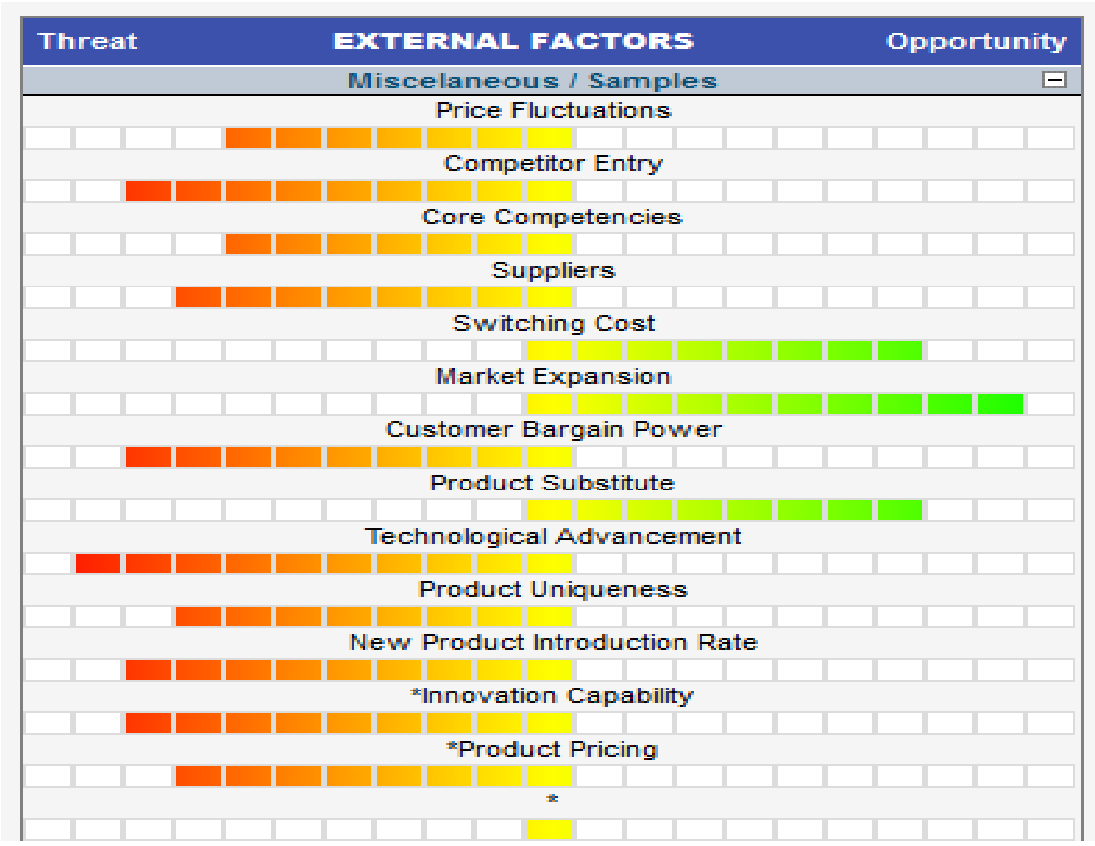


Figure 5.33: Recommended and Normalized Priority Process List

Equipment priority list shown in Figure 5.33 is consistent with the current and future requirements. As the company's most preferred criteria was "Process Economy" so the cheapest process available is CNC which is shown as No. 1 priority. The company targeted volume was low and by considering other related factors, the second preference was Service Bureau. The DSS selected SPRO 230 SLS as the third preference which is Rapid Manufacturing (Direct production of end product) process and offers metallic prototypes with high build volume. This selection is also consistent with the outcome of the IP analysis where lead time and supply chain cost were most critical. The new position of STAF recommends the use of more Rapid Manufacturing to meet the future challenges.

5.6 SPECIFY/Impact Assessment

Once the External Environment and Internal Business Analysis had been completed and suitable process/technology has been identified, the next step is the assessment of likely impact of the selected process on the existing business functions and strategies. The step is accompanied by the identification of opportunities and threats along with their magnitudes. The likely impact of the RP is discussed in detail in Chapter 6. Possible risks of the identified technology were discussed with the management, but no significant risk factor emerged except for the training of the employees. The opportunity and threat analysis was performed as a last step so the company can prepare itself for potential threats and utilize the opportunities they identify through RP technology. For the opportunity and threats, online software called "Inghenia Swot Analysis' was employed to quantify the magnitude of both variables, which can be influenced by the selected technology. Managers were asked to rate the identified factors on 1-10 scale (Low-High) and also identify these factors as either threat or an opportunity. Figure 5.34 shows the identified factors for the opportunities and threats which also includes the factors suggested by Caves and Porter (1977).



Opportunities	Weight
*	10
Market Expansion	9
Switching Cost	7
Product Substitute	7
Total	33

Threats	Weight
Technological Advancement	9
Competitor Entry	8
Customer Bargain Power	8
New Product Introduction Rate	8
*Innovation Capability	8
Suppliers	7
Product Uniqueness	7
*Product Pricing	7
Price Fluctuations	6
Core Competencies	6
Total	74

Figure 5.34: Opportunities & Threats Rating

It is evident in Figure 5.34, that the threats which Company A is facing are much more than the opportunities they have. In reality, if Company A does not address these threats then it will affect their ability to grasp the opportunities they identified. The received score was plotted on a Strength, Weakness, Opportunity, Threat (SWOT) quadrant to locate the current and desired position of the company. Figure 5.35 shows the current position of Company A with a yellow circle and identifies the ideal position, where the company should strive to position itself in future, to maintain a sustainable position in the market, marked by a green circle.

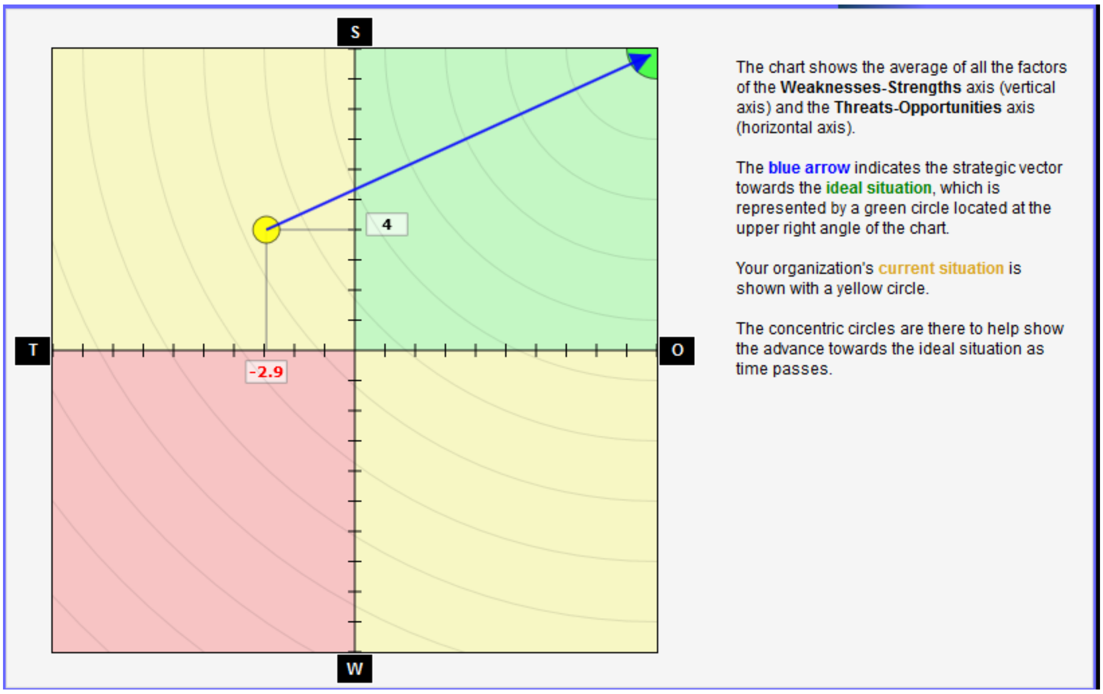


Figure 5.35: Current & Desired Position of Company A

5.7 Concluding Remarks

A comprehensive roadmap for the adoption of RP technology has been demonstrated in this chapter by practical implementation in the real case scenarios. An effective adoption of the technology requires a full synchronization between marketing, strategic and operational functions. Establishment of the link between these functions, determination of the success factors at every single stage, tools and technique development and applications have been discussed in detail. Highlighting the emerging role of RP was also the area of concentration.

The case studies uncovered the shortcomings of the current procedures and exposed why SMEs are not able to address the challenges they are facing on a broader scale.

These include the inability to see the real market picture, lack of understanding of the competitor's capabilities, inadequate information about operational parameters their level of importance and connection with the overall business strategy. Evaluation of the current technology for its ability to produce the desired outcome was insufficient as the technology alternatives that can produce results were unidentified to the top management. The important role of the RP and its ability to resolve various challenges also emerged during the implementation process.

The implementation process provided a practical guide from strategic to operational level and will serve as a template for SMEs for technology adoption. In the next chapter, the results of the case study are described in more detail. The results of the value chain and assessment of the RP impact are also discussed in detail, which will inspire SMEs to review their current procedures and adopt more standardized, clear and quantifiable approaches.

6

ANALYSIS AND DISCUSSION

The primary objective of the study was to develop an integrated RP adoption solution and also to find out the potential of RP technology to assist SMEs in overcoming their strategic and operational challenges. The chapter briefly explains and discusses the results obtained at every single step of the framework operationalisation. Existing strategic product development procedures and operationalisation results of four steps in the RPT adoption framework are also the subject of discussion. The four steps are:

- Market Evaluation & Competitor Analysis
- Internal Business Analysis
- Technology Selection & Evaluation
- Impact Assessment

6.1 Market Evaluation & Competitor Analysis

Market Evaluation responses from Companies A and B revealed that both companies were facing similar challenges like longer time to market, turbulent market demands, and high product customization levels. The companies were also striving for an increased market share. The competitor analysis to determine the competitive position of Company A against its competitors on the four main criteria Competitor objectives, Assumption, Strategy, Capability and fourteen sub criteria (Fig.5.7) are shown in Figure 6.1. The weights of the sub criteria were summed up towards the total weight of the respective main criteria to ease the computation and analysis process.

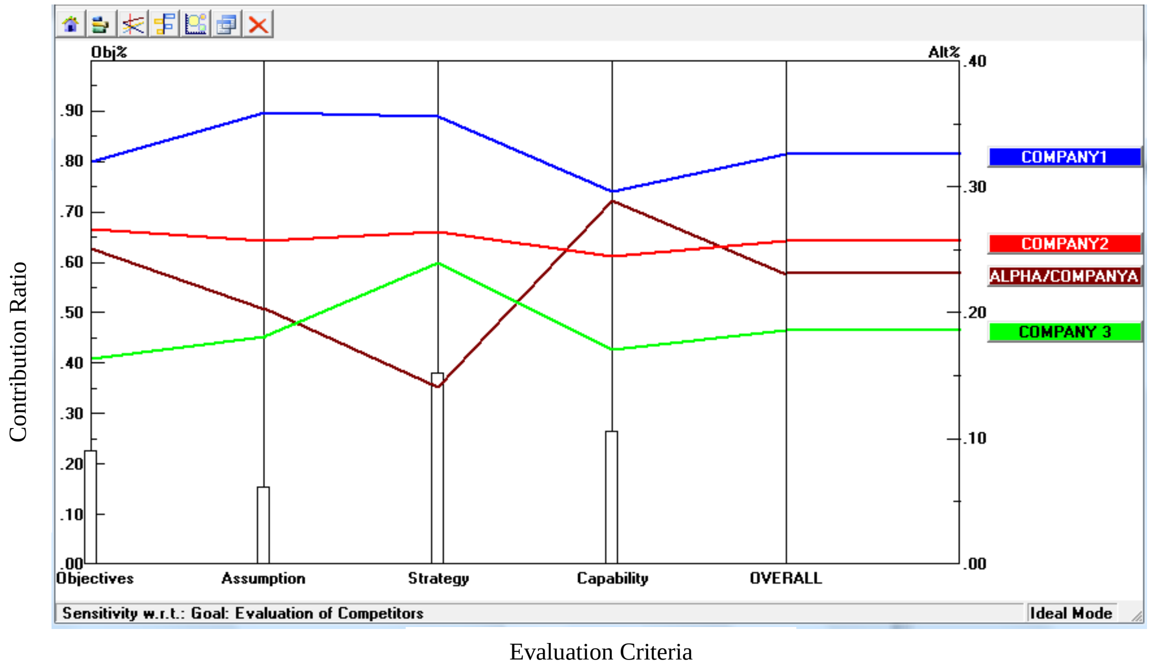


Figure 6.1: Competitor Evaluation Result Company A

It is apparent from Figure 6.1 that competitor strategy was the most dominant and important decision category having a contribution of 37.5%, whereas competitor capability, objectives and assumptions contributed 25.9%, 21.9% and 14.7% respectively. The performance of Company A on competitor strategy was lowest and below company 1, 2 and 3, despite its critical importance. Overall performance of the company was below two of its competitors but was above company 3. Figure 6.2 shows graphically the current position of company A against its competitors.

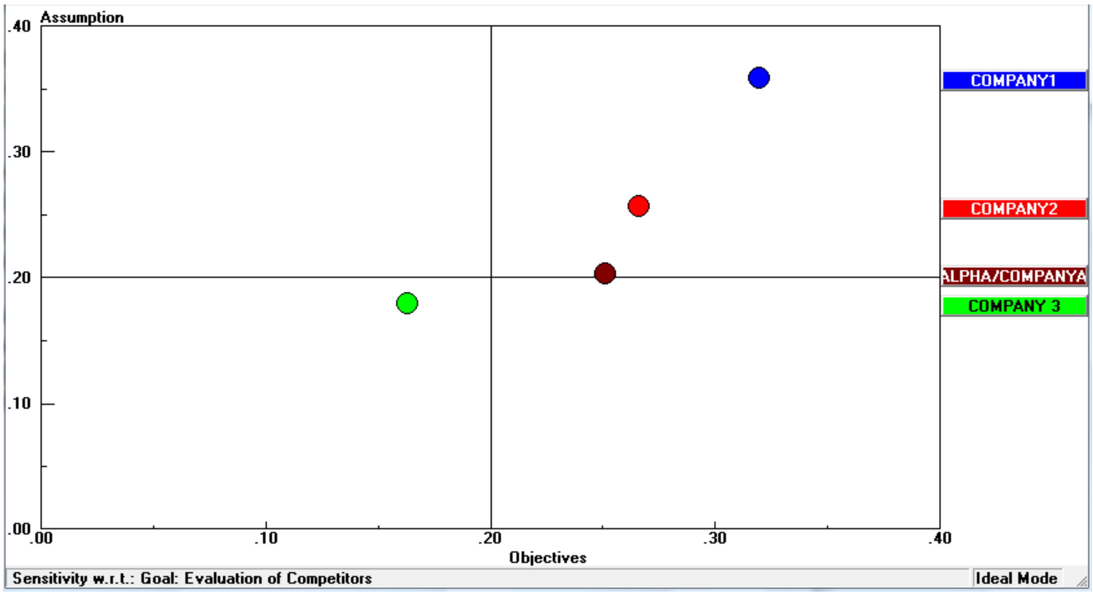


Figure 6.2: Competitive Positioning of Company A in Market

The analysis shows the competitive position of the company and how much effort and in what direction is required to reduce the competitive gap.

For Company B, Competitor Objectives contributed 42.5% importance due to it being more technology intensive business. Competitor strategy, capability and assumption carried 29.2%, 17.1% and 11.2% importance respectively. Figure 6.3 shows the competitor evaluation results of Company B.

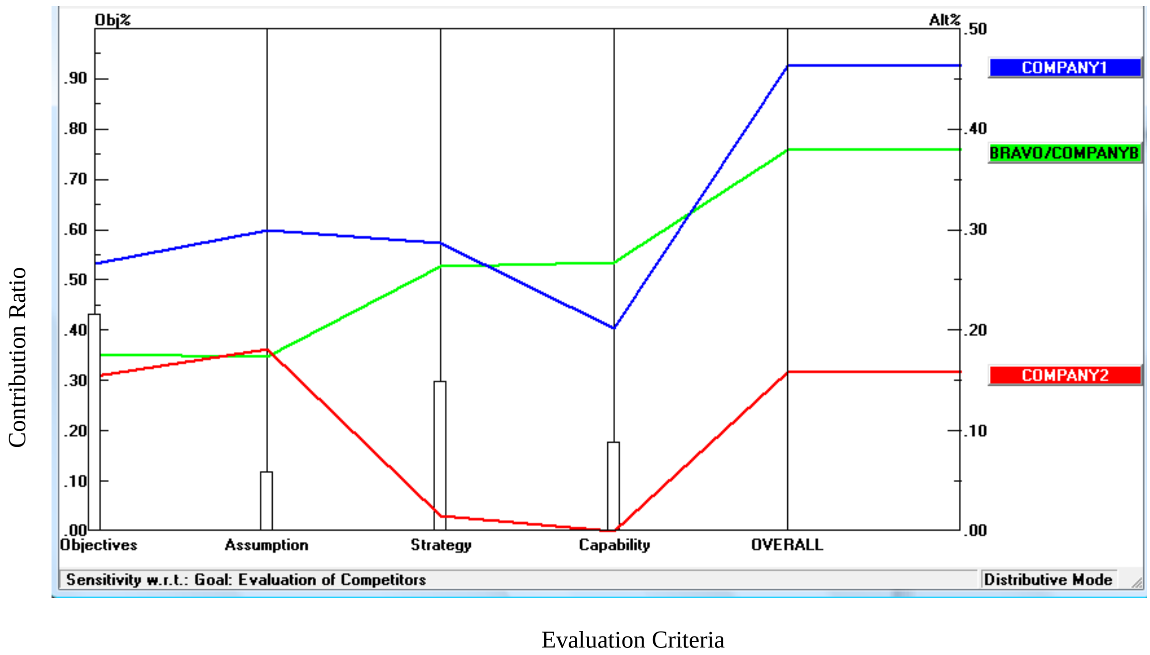


Figure 6.3: Competitor Evaluation Result Company B

It is evident in Figure 6.3 that Company B was lower than Company 1 on competitor capability and objectives domains. Overall performance of Company B was below its main competitor but was better than Company 2. Figure 6.4 shows the competitive position of Company B where performance of the Company 1 is on the outer line of the grid. The result shows a huge gap between company B and its strongest competitor on the competitor objective and assumption domain. This will assist the company in determining the areas where more focus is required to minimize the gaps.

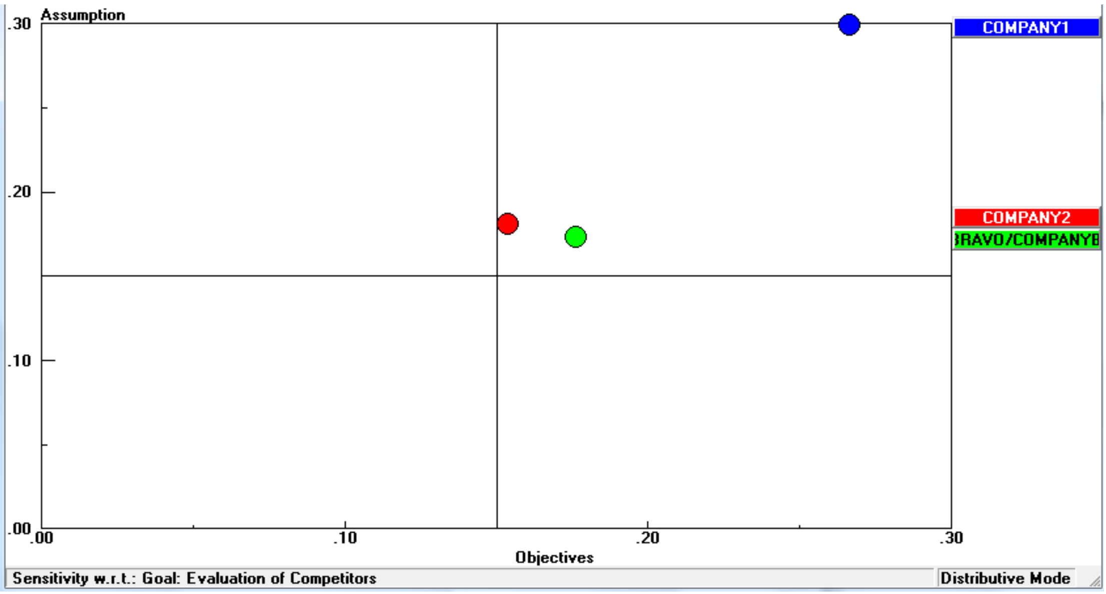


Figure 6.4: Competitive Position of Company B in the Market

Competitor analysis of both companies provided a clear picture of the strategic areas which require improvements for a better market positioning. Any effort to improve operational performance can be ineffective unless the strategic direction is clearly determined and documented.

6.2 Internal Business Analysis

Once the strategic directions had been identified in the first step, the next step was to determine the operational performance and identification of desired operational excellence parameters to better synchronize operations with strategy.

Importance Performance (IP) analysis of Company A revealed that all the factors identified as "Required Urgent Action" were related to Product Development. Some of these factors like Time to Market, Short Life Cycle, Redesign Cost, and Quick

Design Change etc. were linked with early product development cycles resulting from the concept-prototype development. This was the area where RP had the greatest potential to influence.

Company B's operational performance was better than Company A's due to the availability of more resources and better management structure but the time to market and improved product development cycle were again the areas requiring urgent action along with supply chain cost.

Both company's current technological status was put on the Strategic Technology Adoption Framework (STAF) to determine the Strategy-Technology Alignment status. It was revealed that for Company A, there was a great mismatch between current technology and the market demands. The current subtractive based product development process was not capable of delivering the identified strategic output. To achieve the desired outcome, Company A was required to undergo a technological shift from Subtractive (CNC) to Additive (RP) processes to reduce the mismatch.

Company B was outsourcing RP models from a different country, due to which they had issues with supply chain deliveries and long product development cycles. The current position of Company B was plotted on STAF, which suggested that because the company was dealing with novel markets with individual customer requirements, so the focus should be more on RP technology with a shift to Rapid Manufacturing (RM) in the future. RP based RM involves the manufacture of the end product. It was suggested to Company B that they focus on those parts which were perfect candidates for Rapid Manufacturing which can produce the end parts, to compress the product development cycle, which is a necessity of novel markets. Some of the RP equipment are equally capable of producing the end parts.

To develop a deep insight into the product development procedures, a micro value stream analysis was carried out due to a number of reasons:

i) Quantitative verification of the factors identified during the market assessment and IP analysis through detailed analysis of current manufacturing operations.

ii) To improve the current practices by discovering the pitfalls and weaknesses in the current way of doing business.

iii) To develop a VSA template as a guide, to assist SMEs in the analysis of business operations.

iv) To determine the role of the RP at every single step of product development and manufacturing operations to emphasize its importance.

The breakdown of the activities in shelter manufacturing and proportion of their contribution have already been explained in previous sections. Contribution of VA, SVA and NVA activities and listing all the activities in these three categories, was the real purpose of this analysis. The contribution of VA, NVA & SVA in shelter manufacturing is shown in Figure 6.5.

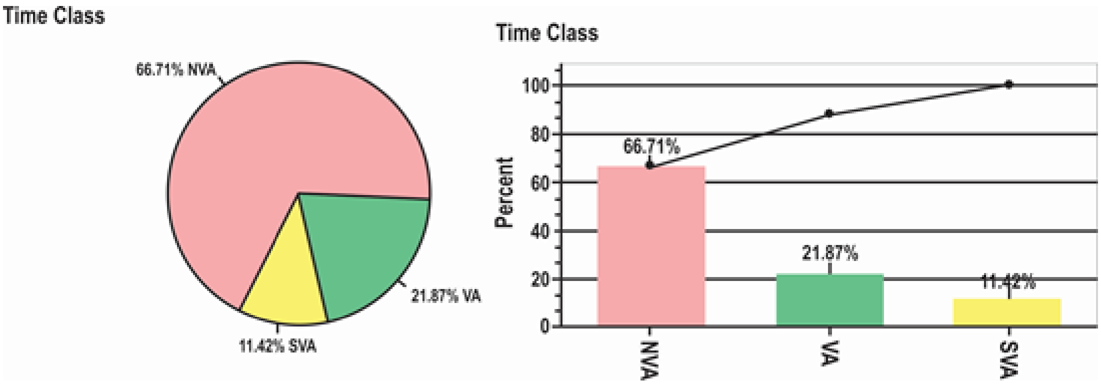


Figure 6.5: Contribution of NVA, VA, SVA in Shelter Manufacturing

Figure 6.5 shows that for the complete project from idea generation to the manufacturing of the first product 66.71% of activities were mutually declared as NVA whereas 11.42% were considered as SVA. Only 21.87% of the time and resources were spent on VA activities. These results show why the company was not able to effectively address the market challenges and resulted in a long list of factors which required urgent action in IP analysis. This situation demanded further analysis to see what actually constituted these categories. Further classification of the VA category is shown in Figure 6.6.

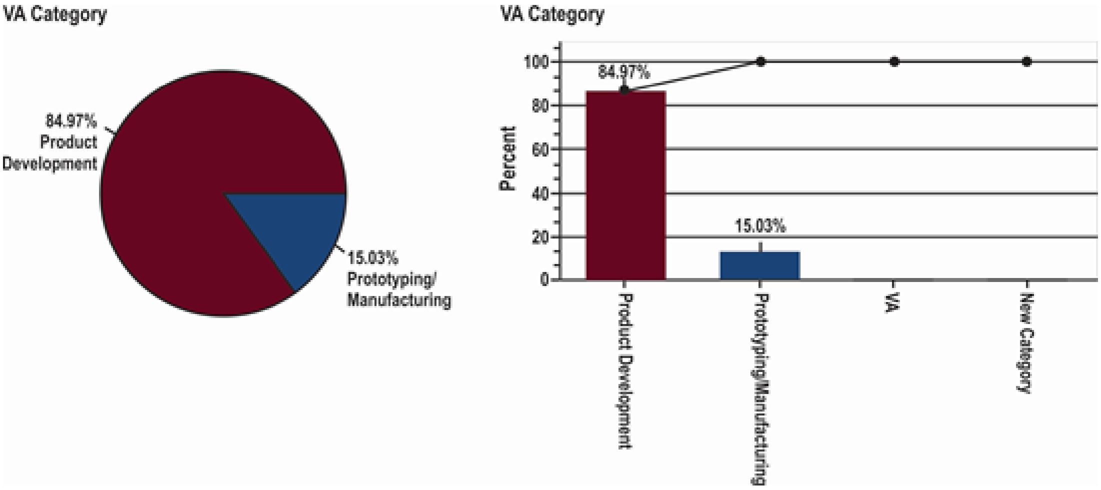


Figure 6.6: Classification of VA Activities

This revealed that 84.97% of time was spent in product development, whereas 15.03% contributed to the prototyping and manufacturing of the parts. Further classification of NVA activities was also essential to understand, so as to identify what contributed to this group for the sake of improvement actions in future. Figure 6.7 shows the further classification of NVA activities:

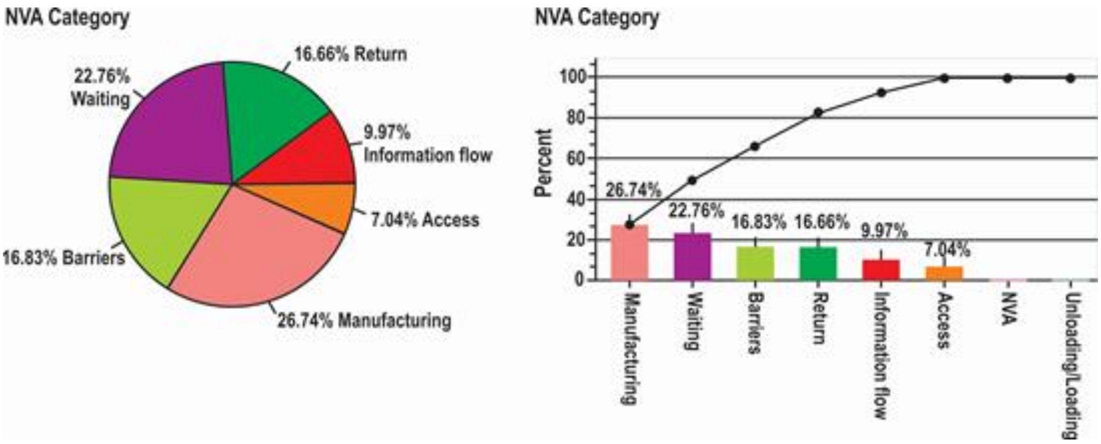


Figure 6.7: NVA Activities and their Contribution

It is obvious in Figure 6.7 that 26.74% of NVA activities were performed during the manufacturing stage which includes lack of complete design and related process information. 22.76% of the time was spent on waiting which included design finalization, amendments and missing information. This caused delays in upstream processes like tools and machine designs for the desired products. 16.83% of time was lost due to the traditional barriers like behind the wall approach, failure to involve the client during design and lack of manufacturing involvement during design which resulted in several design failures. Returns were another class which contributed 16.66% of NVA time. Returns occurred at many stages of the process including returns by customers due to design problems, returns by the manufacturing department at later stage due to their inability to manufacture as manufacturing abilities were not considered during the design phase. 9.97% of time was spent on information flow, which was unnecessary and could be avoided if RP technology was utilised. RP reduces reworks which ultimately reduces the information flow.

SVA activities and their contribution are shown in Figure 6.8. It indicates that 51.75% of time was spent on quality related tasks and 48.29% was spent on design related SVA activities.

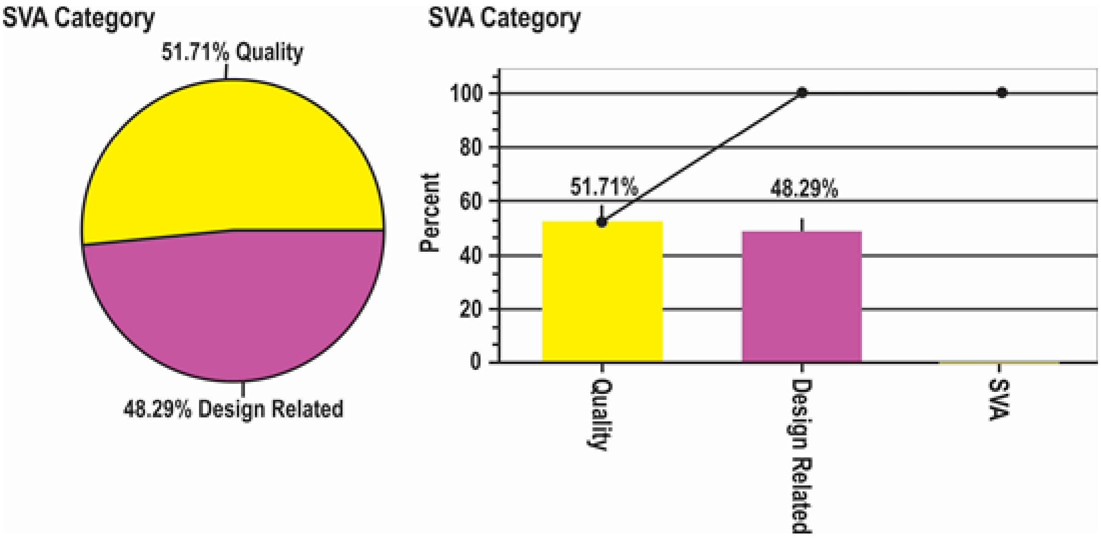


Figure 6.8: SVA Activities and their Contribution

The time spent on these activities cannot be completely eradicated but has the greatest potential to be minimized.

This step showed how much time and resources were spent on every group of the overall project. An analysis of the total project is shown in Table 6.1 showing the time taken for each activity, its cost and how much distance it covered.

The table shows an approximate cost of Rs. 3.648 million, which is close to the cost of Rs. 3.6 million provided by the General Manger. This was the cost of producing the first shelter from the idea generation to the first manufactured product.

Table 6.1: Aggregate Summary of Shelter Project

SIMPLE AGGREGATE SUMMARY : Year

AGGREGATE	FROM	TO	FREQUENCY	TOTAL DISTANCE FEET	TRIP DISTANCE FEET	EFF. TRIP DISTANCE FEET	TRAVEL TIME SECONDS	L/UL TIME SECONDS	TOTAL TIME SECONDS	TRIP TRAVEL TIME SECONDS	COST Rupees
TELECOMSHELTER	CLIENT	MARKETING	10.00	455.00	45.53	45.50	455.34	1,296,000.00	1,296,455.34	45.53	12,604.43
	MARKETING	CLIENT	10.00	455.00	45.53	45.50	455.34	864,150.00	864,605.34	45.53	60,042.04
	CLIENT	MARKETING	20.00	910.00	45.53	45.50	455.34	1,728,000.00	1,728,455.34	22.77	12,003.16
	MARKETING	GMOPR	30.00	1,569.90	52.37	52.33	785.50	2,592,000.00	2,592,785.50	26.18	25,207.64
	GMOPR	CEO	20.00	1,015.00	50.79	50.75	1,015.77	1,732,000.00	1,733,015.77	50.79	16,848.76
	CEO	CLIENT	5.00	450.85	90.13	90.17	450.65	432,500.00	432,950.65	90.13	8,418.48
	CEO	FINANCE	7.00	337.19	48.16	48.17	337.11	907,200.00	907,537.11	48.16	25,209.36
	CEO	DESIGN	40.00	2,296.80	57.44	57.42	2,297.75	6,920,000.00	6,922,297.75	57.44	384,572.10
	PM	DESIGN	20.00	783.40	39.19	39.17	783.74	2,592,000.00	2,592,783.74	39.19	57,617.42
	DESIGN	GMOPR	40.00	1,806.80	45.18	45.17	1,807.07	5,184,000.00	5,185,807.07	45.18	86,430.12
	GMOPR	CEO	20.00	1,015.00	50.79	50.75	1,015.77	4,320,000.00	4,321,015.77	50.79	180,042.30
	CEO	MANF	5.00	1,786.65	357.35	357.33	1,786.77	648,000.00	649,786.77	357.35	451,240.80
	DIEMAKING	MOLDING	12.00	932.04	77.64	77.67	931.68	5,184,000.00	5,184,931.68	77.64	360,064.70
	MOLDING	FILLING	20.00	1,431.60	71.60	71.58	1,432.05	1,456,000.00	1,457,432.05	71.60	202,421.10
	FILLING	MACHINING	20.00	1,143.40	57.21	57.17	1,144.11	4,320,000.00	4,321,144.11	57.21	480,127.10
	MACHINING	PAINTING	15.00	486.30	32.41	32.42	486.16	2,790,000.00	2,790,486.16	32.41	193,783.80
	PAINTING	SUB-ASSEMBLY	100.00	7,525.00	75.27	75.25	7,526.74	12,960,000.00	12,967,526.74	75.27	180,104.50
	PM	GMOPR	10.00	479.20	47.89	47.92	478.91	1,296,000.00	1,296,478.91	47.89	270,099.80
	GMOPR	ASSEMBLY	5.00	1,956.65	391.35	391.33	1,956.75	648,000.00	649,956.75	391.35	135,407.70
	ASSEMBLY	OFFICE	3.00	1,100.49	366.86	366.83	1,100.58	388,800.00	389,900.58	366.86	54,152.86
	OFFICE	ASSEMBLY	20.00	7,336.60	366.86	366.83	7,337.19	5,200,000.00	5,207,337.19	366.86	433,944.80
	CLIENT	ASSEMBLY	5.00	2,041.25	408.23	408.25	2,041.17	648,000.00	650,041.17	408.23	18,056.70
SUB TOTAL			**437.00**	**37,314.12**			**36,081.49**	**64,106,650.00**	**64,142,731.49**		**3,648,399.67**
TOTAL			**437.00**	**37,314.12**			**36,081.49**	**64,106,650.00**	**64,142,731.49**		**3,648,399.67**

The data in Table 6.1 shows the cost and time break down of the activities employed for the completion of the project. It provides a clear picture of the product development process and the issues associated with this critical stage. A major proportion of the resources were spent before any formal manufacturing started.

The results of the VSA show the hurdles and extreme waste of time and resources, which ended up with customer dissatisfaction. The analysis also exposed the limited abilities of the current business procedures and clearly identified why the business was not able to meet its strategic objectives due to its weak operational performance. Adoption of the new technology was recommended by STAF as one way to meet its strategic goals. The next step describes the selection and evaluation results of the RP technology.

6.3 Technology Selection and Evaluation

It emerged during external and internal evaluation processes that the current process and technology was inadequate to provide Company A with a competitive position in the markets. The current technology was also found to be unable to address the identified challenges effectively. Strategic Technology Adoption Framework (STAF) suggested shifting the focus towards RP technology for an efficient product development programme.

The top priority of Company A was to select the most economical technology from all aspects and at the same time be able to offer a desired improvement in operational performance. The recommended priority graph of selected RP equipment based on the Company A input is shown in Figure 6.9.

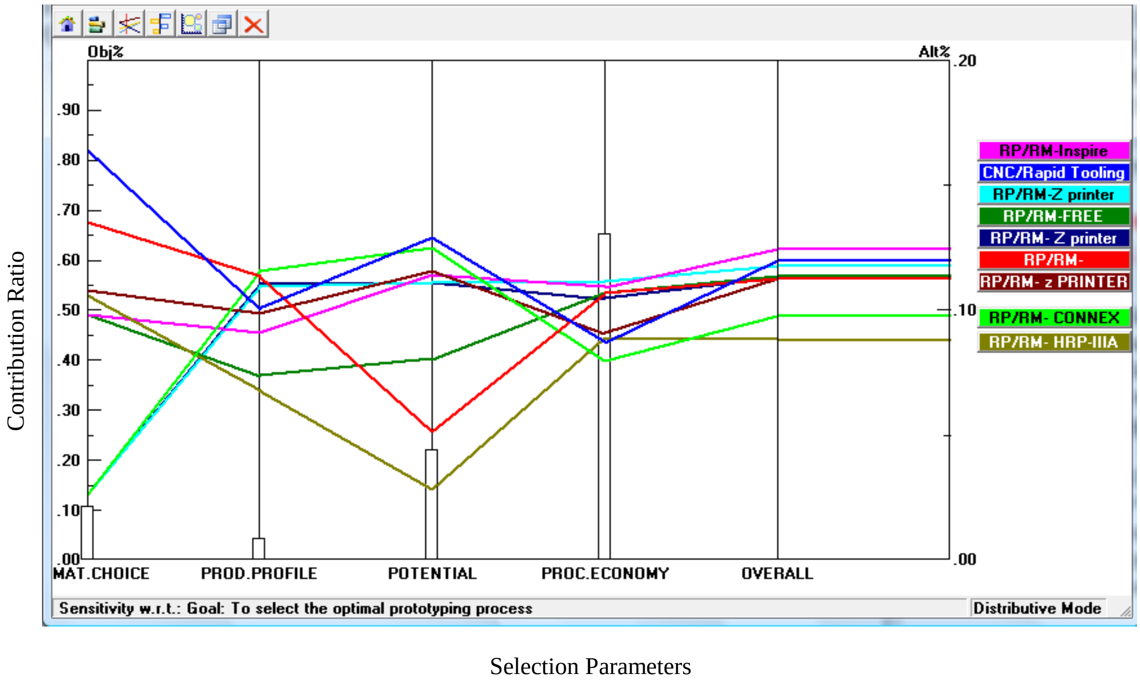


Figure 6.9: Technology Selection Outcome Company A

The priority graph shows the weights of the selection factors as vertical bars, whereas the relative score of the alternatives are shown with colour lines and arranged on the right based on the overall priority. Figure 6.9 shows Inspire as the top recommended system. For the sake of verification, all its properties were manually verified against the data collected, which revealed that the cost of the system was only $10,000, whereas material cost was around $175/kg and the equipment was capable of delivering the company's requirements.

Sensitivity Analysis of the decision is shown by What-If analysis provided in Figure 6.10. The graph enables one to test the sensitivity of the decision by changing the priorities to observe the impact on the decision. By dragging the priority values at the left, the priority values on the alternative were also changed. For example, if the company changes the ranking and focuses more on Process Economy than Product Profile the resulting Process Economy ranking increases from 48.7% to 64.6% whereas the Product Profile decreases from 27.5% to 3.8% as shown in Figure 6.10. The sensitivity of the decision can be determined in relation to the impact on the selected equipment and in this case the Inspire again emerged as the top selection. This shows that the decision is stable and that minor changes in preferences do not impact on the selected equipment. This validates the previous findings and shows that the selection is appropriate for the desired objectives of the company.

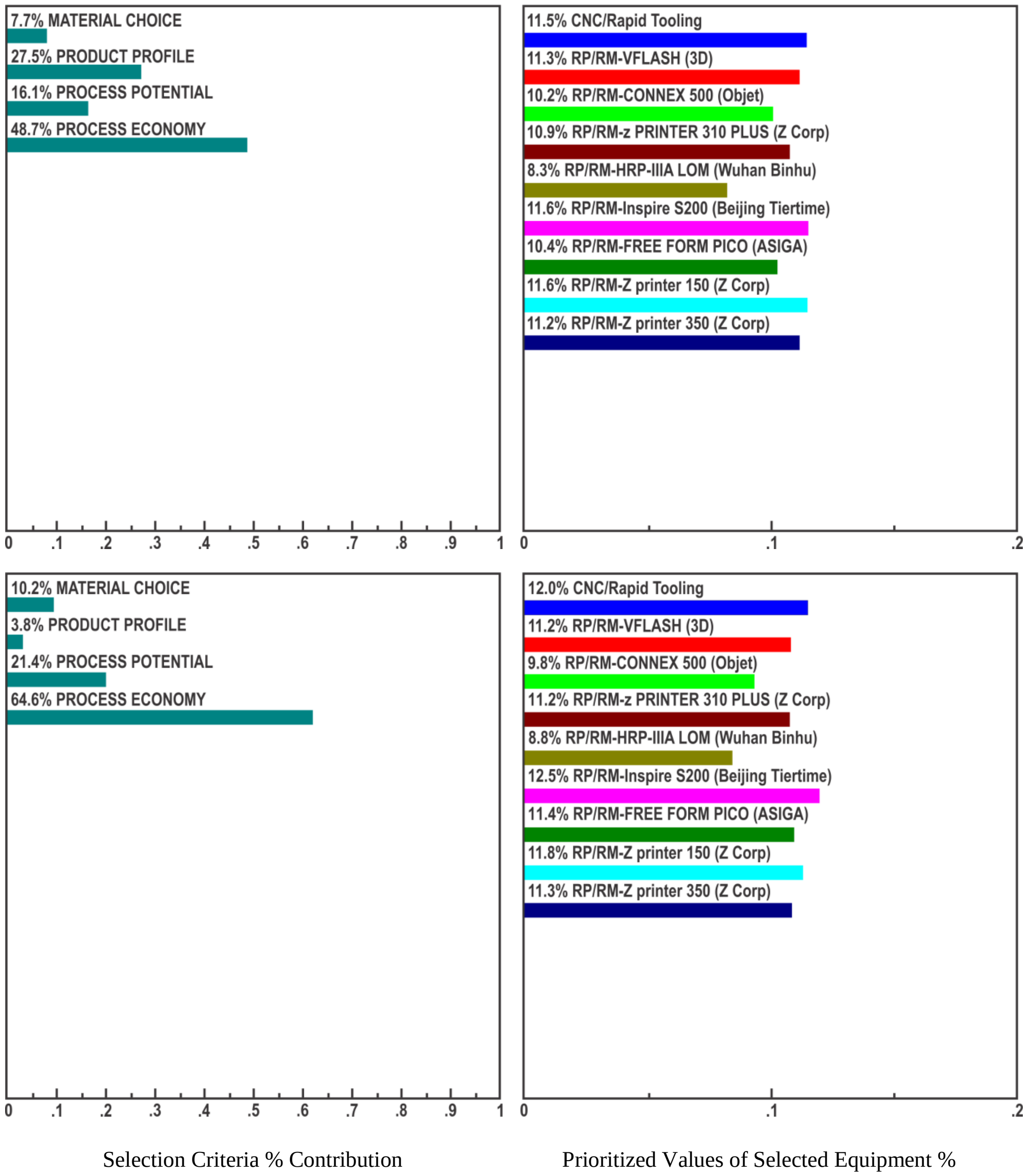


Figure 6.10: What-If Analysis of RP Equipment Selection

Figure 6.9 provides a list of equipment based on the overall criteria and ranking calculations however sometimes it is necessary to compare technologies against only a single parameter. The DSS can compare all the equipment even against single criteria. This is shown in Figure 6.11 which shows the preferences of the alternative against a single parameter Equipment cost.

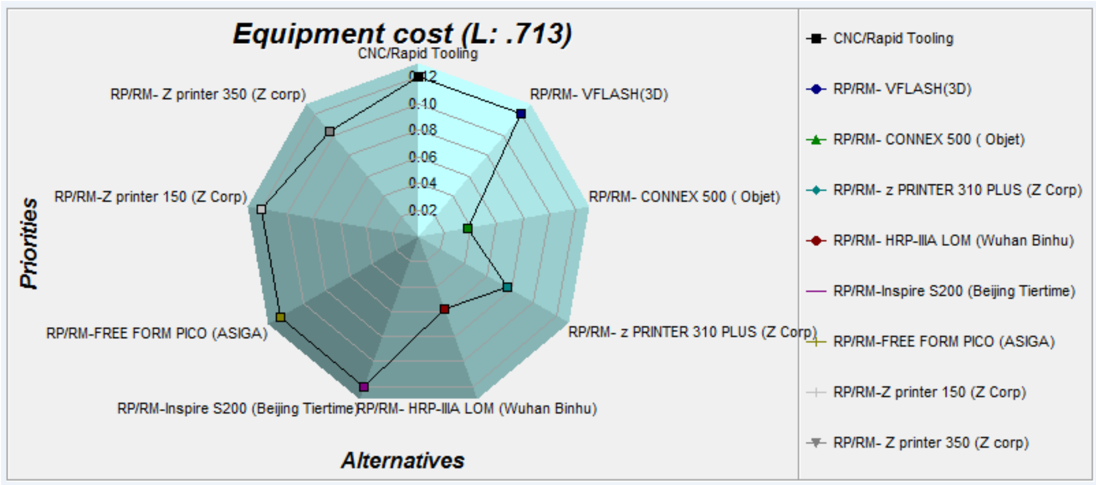


Figure 6.11: Alternative Priorities with respect to Equipment Cost

A detailed comparison of the equipment having close priority rankings is also required to see how the selected equipment performs against the main criteria. Figure 6.12 shows the head to head comparison of Inspire with CNC, showing that CNC is preferable on certain parameters but these parameters were not important for the user, which resulted in overall high scores in favour of Inspire.

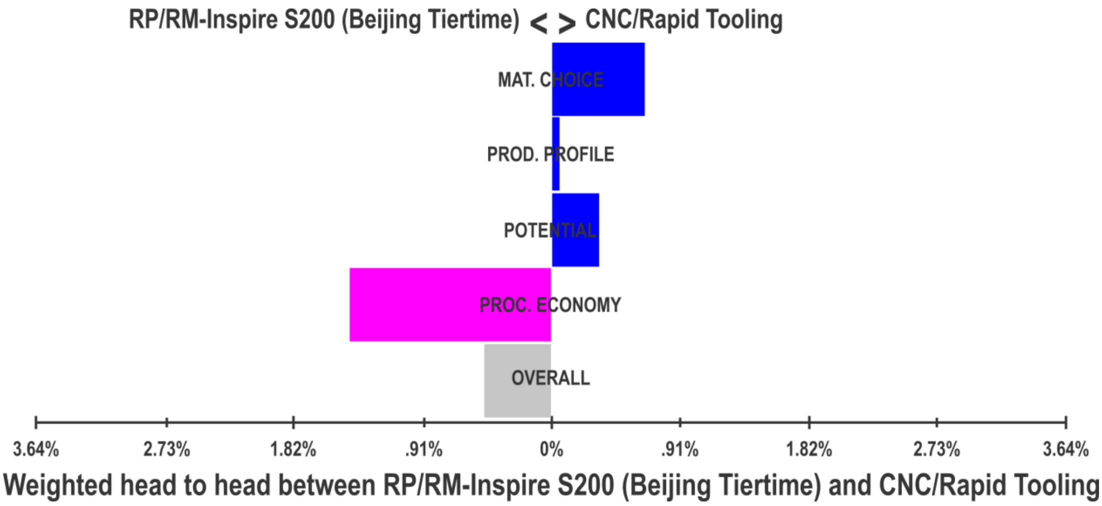


Figure 6.12: Head to Head Comparison of CNC & RP Inspire-200

Similar comparison is possible between any two selected alternatives for the purpose of detailed evaluation of the selected technology against its nearest rivals before any formal technology acquisition decision is made.

DSS was also employed for the selected product of Company B to select the right technology. The results show that the process economy obtained 45.6% performance whereas Material Choice, Product Profile and Process Potential received 33.3%, 13.4% and 7.7% priority by the user respectively. The result of the selected equipment is shown in Figure 6.13.

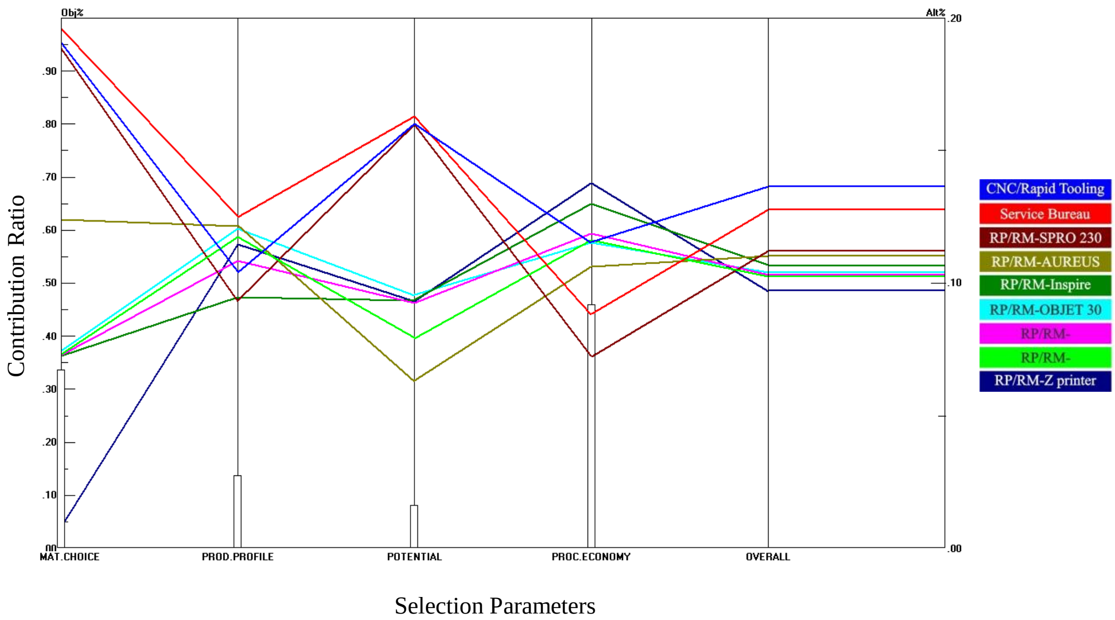


Figure 6.13: Technology Selection Outcome Company B

The result validates the current operational abilities by suggesting the use of CNC and the service bureau. It was identified during Market Evaluation and IP analysis that the company was facing tremendous challenges with supply chain cost along with reduced Time to Market. Positioning of the company on STAF also suggested more reliance on RP and a shift in focus from RP to Rapid Manufacturing of end parts where possible to synchronize with rapidly changing market dynamics and customer demands. Figure 6.13 highlights the list of possible equipment, as the company top priority was the metallic materials based RP technology. Since the RP equipment is capable of producing metallic prototypes, but are quite expensive, the Decision Support System suggested the use of SPRO 230 SLS, which is the cheapest available in the metallic range and can handle Rapid Manufacturing of end parts in certain cases. The selection was in line with the Company B input which gave highest preference to the process economy.

The next section explains the likely impact of RP on product development process.

6.4 Impact Assessment/Specify

The impact of RP on business can be grouped into qualitative and quantitative aspects. The qualitative impact was better understanding of customer demands, increased ability of the company to have an enlarged market share, increased customer confidence and improved competence of the business for a better quality and faster product. The qualitative parameters ultimately convert into quantitative financial gain as the company's market share increases. All the data collected during the Pro Time Estimate and Flow Analysis were plotted to determine the likely impact of RP. The quantitative impact of the proposed RP intervention was quite clear and convincing. Company A faced tremendous challenges during the product development and manufacturing stages. The product development cycle was quite long, where at several stages the customer showed mistrust on the ability of the company to complete the project successfully as told by the management. Figure 6.14 summarizes the complete product development time.

Based on the complete VSA of the entire shelter projected mentioned in section 5.4.3, Figure 6.14 gives a very clear picture of the impact that RP can have on the complete product development time. It is evident from the figure that the classic product development time was around 105 days, which gives a good reason behind the challenges that emerged during IP analysis. With the intervention of RP, the company can shrink the product development cycle to approximately 42 days, which can have a great impact on the life of the whole project. The manufacturing stage was not free of issues. There were several problems encountered by manufacturing engineers as they were not consulted and whatever they suggested was not possible to be manufactured.

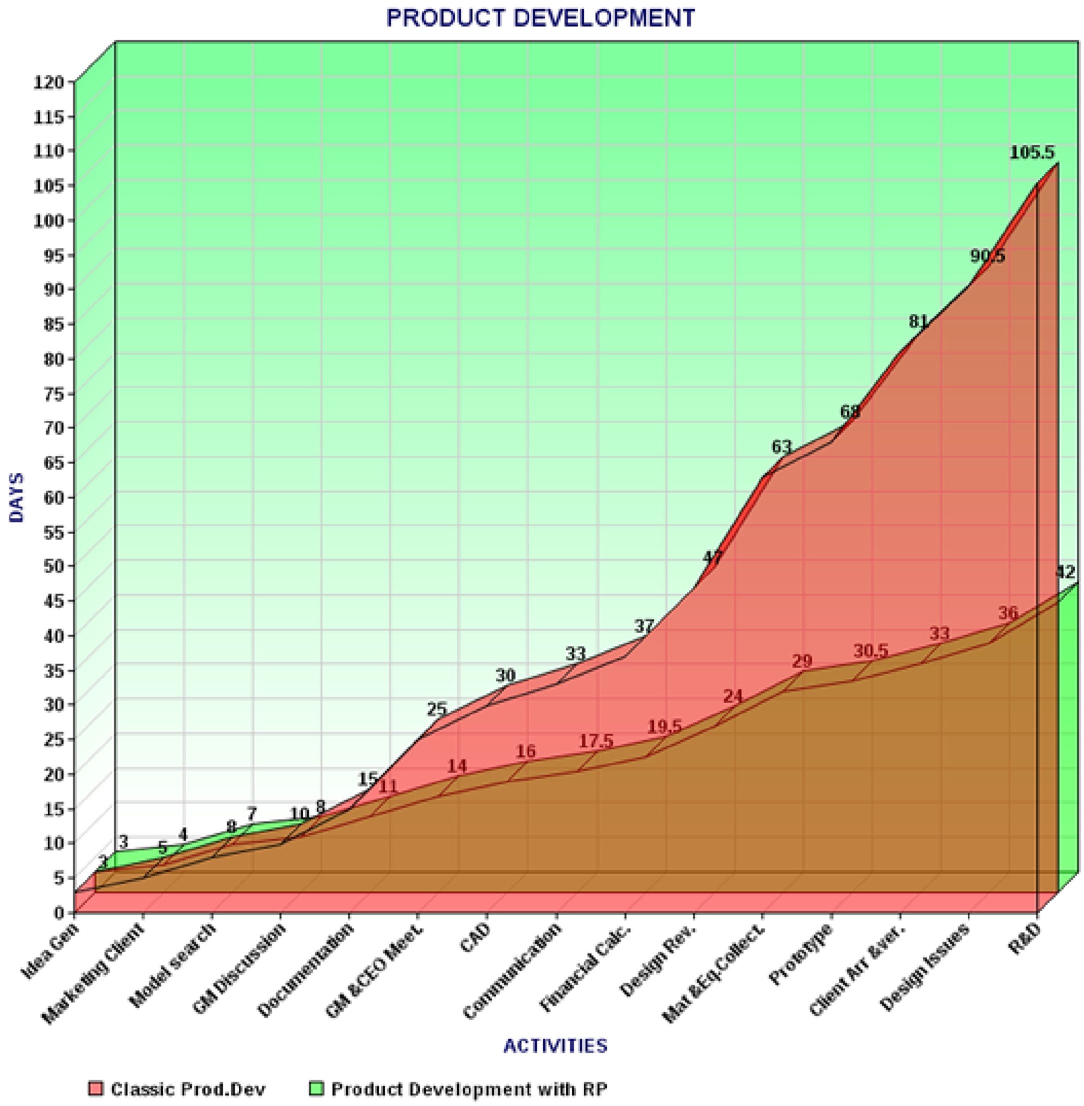


Figure 6.14: RP Impact on Product Development Time

The customer also suggested many revisions which increased the manufacturing time and cost. Estimated cost of the project along with the cost with RP intervention is shown in Figure 6.15 where the separate cost of product development and manufacturing is clear.

The cost increased sharply during manufacturing due to several manufacturing related issues, which must be resolved during product development stage. The delay in product development had a significant impact on the entire life cycle particularly during the manufacturing phase.

To deliver the project on time, 24 hours of manufacturing in three shifts was introduced and 30-35 more skilled workers were employed on an ad-hoc basis. Due to this reason the manufacturing cost increased many times which was outside of the plan of the company. The cost impact of RP is also shown in Figure 6.15 showing a very smooth transfer between each phase, resulting in a much reduced cost.

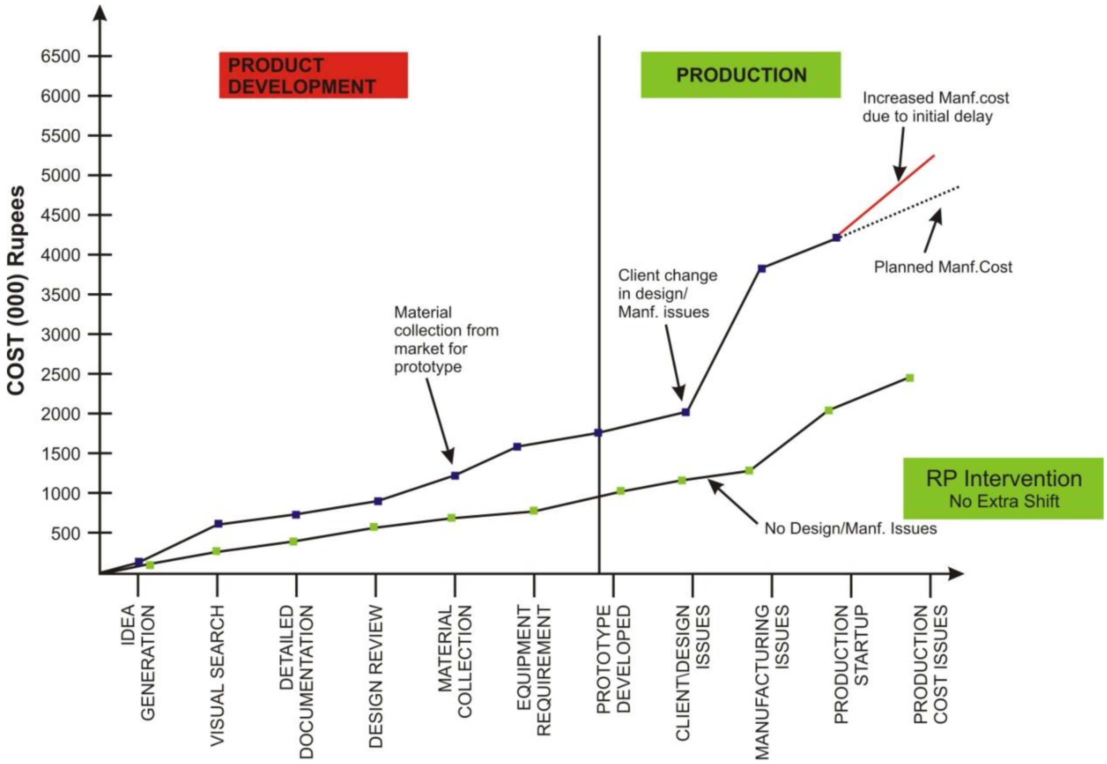


Figure 6.15: Cost Impact of RP on Shelter Development Project

Figures 6.14 and 6.15 clearly indicates the rationales behind the challenges and issues identified during the external market evaluation and IP analysis phase and also highlights the critical role that RP technology can play by overcoming the identified challenges. All the issues faced during the product development and manufacturing stages can be reduced if RP technology was employed. The quantitative benefits which were possible to achieve include the redesign cost, shorter introduction time, improved manufacturing with qualitative advantages like satisfied customer and improved operational synchronization. The new role can lead towards an increased market share.

6.5 Concluding Remarks

Selection of the RP technology, linking it with business and marketing strategy and understanding its real impact on the life cycle are few of the issues which were identified as potential barriers to be overcome prior to the successful uptake of RP technology. Absence of any practical guidelines has resulted in dangerously low adoption levels in SMEs particularly in developed countries.

A comprehensive adoption process for RP technology has been demonstrated in detail during practical case studies. The guide provides practical solutions from strategic to operational level by the application of several tools and techniques. The impacts of the RP on the complete life cycle of the product have been quantified by the detailed analysis of a real project. The micro analysis has highlighted the role of RP in achieving business goals and will ease the adoption decision for manufacturers. The development and use of a comprehensive selection tool for the selection of the right system has also been demonstrated by taking the input from the companies.

An overall summary of the findings and results has been provided in the following chapter.

7

CONCLUSION AND FUTURE DIRECTIONS

7.1 Conclusion

This study presents a comprehensive practical roadmap for the adoption of RP technology. The proposed procedures have been supported by several frameworks, techniques and a Decision Support System to facilitate technology selection. It has been shown that such development was vital to assist SMEs to modify and review their traditional procedures if they want to survive and compete in future markets. The challenges discovered during the practical work and literature survey can be summarized as:

- Inadequate research, reliance on conventional procedures, resistance to change which increases several times in the absence of convincing solutions.
- No formal procedures exist for market evaluation and strategy formulation technology selection based on strategic direction.
- Studies which can demonstrate the technology link between marketing and business strategy were limited and their application in particular cases was hard to find.
- Selection of the right RP technology based on the user requirements is a major adoption barrier.

- Technology is surrounded by myths and often the end user is uncertain as to its potential impact on the business and operations.
- The nature of the SMEs in fact requires a systematic but practical approach.

A comprehensive two-phase approach has been developed in this research and has been shown to be effective for RPT selection. The first step developed a comprehensive RP adoption framework. The framework provides all the steps required for an effective RP adoption from strategic to operational levels. It also details all the processes required along with their potential output/ outcomes. In the second phase, a practical method was developed through implementation of the developed tools & techniques through real case studies. This provided a comprehensive adoption system which will be a significant support for SMEs. Introduction of Effective Technology Adoption terminology and its detailed implementation mechanism was a key achievement in the area of technology selection, which allowed for a better understanding of adoption procedures and entails an ideal technology fit. The implementation process also ensures that the selected technology links with all business functions. The other advantages include:

- Quantification of factors, which were considered qualitative and were hard to determine. For example, Competitor analysis which ranked the qualitative criteria and gave a true sense of the competitive positioning.
- Identification of RP drivers, which eventually were converted into functional evaluation criteria. The developed criteria were utilized during Importance Performance Analysis.
- Developed Strategy Technology Adoption Framework (STAF) depicted a very clear correlation between the technology & strategy and was able to identify the gaps or mismatches between two strategies.
- A novel approach to micro value chain analysis was developed which was able to handle the product development analysis at the micro level. The approach not only highlighted the emerging role of RP but also exposed the pitfalls in the current procedures. This can provide a starting point for any improvement initiatives.

- An open ended Decision Support System was developed which was able to produce a prioritized list of selected equipment. The system was based on both quantitative and qualitative inputs from the individual user. The knowledge base of the developed DSS can accommodate all the advancements of RP in future.
- The impact of RP was quantified which will facilitate the technology related decisions for those who believe that technology is irrelevant for them.

A deceptive phenomenon which was observed during the case study was where the company compared itself with the nearest competitor and gave false readings about its competitive position, without understanding the fact that a competitor might not be a good performer. This means that if a better performer is compared with an average one, then it cannot be declared excellent or fully satisfied. In reality, they are both ignorant of the rapidly changing global value chain demands. This is similar to an aircraft whose speed instruments are showing high speed, but actually the plane is stalling. In both cases they can end up with failure if not recognised early enough. When such companies get an opportunity to take a share in GVC, their lack of understanding or competence simply hinders them from capturing this market share. The essential requirement is not only to compare with their nearest competitor but also to the changing demands of the GVC. If they meet with such opportunities, they find themselves aware and ready.

Most of the previous studies regarding the technology selection were developed on the assumption that the adopter has a complete understanding of the features and capabilities of the potential technology. However the reality was it was discovered that it was totally unknown to the company.

The total cost of product development emerged to be around Rs. 3.6 million for company A. Out of all the activities carried out; around 62% of them were declared Non Value Adding, which meant a waste of around 2.2 million rupees. The cost of the RP system recommended by the DSS was around Rs. 1.00 million, which automatically gave the financial justification of the purchase along with other qualitative benefits.

7.2 Academic and Industrial Contributions

Technology Roadmapping is a needs based technique, which can be developed once the clear need is identified. In the case of RPT roadmapping, a clear requirement of the SMEs was established and the contents of the framework were selected carefully for a systems based approach.

There were several frameworks developed to support the study, along with a complete mechanism for adoption equipped with required tools and techniques. This will not only add to the previous body of knowledge in the area of Technology Adoption but will also provide new directions in this critical research area. The research can be modified or replicated to other technology related issues and even can be used by Governments or regulatory bodies for the complete assessment of the technology before it can be introduced. The research also quantified the impact of RP and its role in achieving the business goals through novel techniques.

The practical impact of the study is much higher than just theoretical contribution. The research clearly answers two questions which were considered critical barriers behind the slow adoption. The first was "why one should use this technology". The micro value chain analysis and initial analysis clearly answered this question which will help to eradicate myths which were stopping this sector from using the technology. Once they are convinced, the second critical question was "what they have to do". This has also been answered clearly by a proposed step by step approach.

This will help tens of thousands of SMEs, to make better decisions, to review and improve practices and to consider emerging technologies to address the challenges they are facing.

7.3 Future Research

The new technology is still emerging where new and cheap materials are being introduced at a rapid pace and at the same time the focus is shifting from Rapid Prototyping to Rapid Manufacturing. These studies should be modified in the future to accommodate and to take full advantage of new developments. The knowledge base of the Decision Support System for technology selection is also required to be updated to accommodate the capabilities and potential of the newly introduced technologies. The proposed model is flexible and can be used to incorporate more RP systems. This will ensure that the latest equipment is selected when the procedure is deployed. At this stage, the risk calculations were minimal as no significant risk was identified but in the future risk should be considered due to the introduction of new materials and technologies.

Due to the emerging status of the technology, most of the research focus is on the technological development, whereas the technology diffusion studies have not received significant attention. The success stories are still surrounding the large companies like Boeing, BMW etc. whereas a large proportion of industry is still not able to reap the benefits. More diffusion will ultimately result in promoting avenues of research and advancement in technology.

8

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APPENDIX A

COMPETITIVE PROFILE MATRIX (CPM)

Rating 1-7 where 1 = Poor & 7 = Extremely Good

	Critical Success Factors	C1/RATING	C2/RATING	C3/RATING	C4/RATING	COMPANY/ RATING
1	Financial position					
2	Market Share					
3	Technology Leadership					
4	Belief about competitive position					
5	Past experience with the product					
6	Industry Trends					
7	R&D Projects					
8	Capital Investment					
9	Promotional Campaign					
10	Strategic Partnership					
11	Technological Capability					
12	Operational Performance					
13	Product acceptance					
14	Product Quality					

APPENDIX B

Company Introduction and Market Evaluation Review

Objectives:

a) Introducing the purpose of study, background and road mapping approach.
b) Identify the Company Objectives.
c) Evaluate the current markets, competitive dimensions and indicators.
d) Competitor evaluation criteria, ranking and company position in the market.
e) Opportunities and Threats of the external and internal environment.
f) Gap identification and mismatches if any between current company status and the environment in which it operates.

MARKET EVALUATION QUESTIONAIRE

Purpose:

The purpose of this questionnaire is to identify the market nature to get a clear picture of the external environment, forces and challenges.

Questions:

i) The nature of market

- High Standardization
- Medium Standardization
- Differentiation
- Personal

ii) Product Customization Levels

i) Limited
ii) Moderate
iii) High
iv) Individual requirements

iii) Product Complexity Level

- Very High
- High
- Medium
- Low

iv) Product Flexibility Demand

1) Low
2) Moderate
3) High
4) Quick

v) Time to market requirements

i) High
ii) Moderate
iii) Low
iv) Very Low

vi) Market condition

i) Highly Stable
ii) Stable
iii) Turbulent
iv) Novel

vii) Product Volume demand

1) Very High
2) High
3) Medium
4) Low /Single units

viii) Most Important outcome of the business?

a) Increased market share

b) Improved customization ability

c) Lead time reduction

d) Quality with low price

ix) Does technology play a critical role in achieving business goals?

x) What procedures are in place for the selection of technology?

xi) Which factors are critical for the selection of technology?

xii) Any documented procedure for product development and realization in place?

xiii) Any formal manufacturing audit in place?

APPENDIX C

Technology performance and importance evaluation criteria

	Order-winning objectives:	**NINE POINT IMPORTANCE FACTORS**
1)	Provide a crucial advantage with customers - they are the main thrust of competitiveness	
2)	Provide an important advantage with most customers - they are always considered by customers;	
3)	Provide a useful advantage with most customers - they are usually considered by customers;	
	Qualifying objectives:	
4)	Need to be at least up to good industry standard;	
5)	Need to be around the median industry standard;	
6)	Need to be within close range of the rest of the industry;	
	Less important objectives:	
7)	Do not usually come into customers' consideration, but could become more important in the future;	
8)	Very rarely come into customers' considerations;	
9)	Never come into consideration by customers and are never likely to do so	
	In this market sector, or for this product group, is our achieved performance in each of the performance objectives:	**NINE POINT PERFORMANCE FACTORS**
	Better than competitors:	
1)	Consistently considerably better than our nearest competitor;	
2)	Consistently clearly better than our nearest competitor;	
3)	Marginally better than our nearest competitor	
	The same as competitors:	
4)	Often marginally better than most competitors	
5)	About the same as most competitors;	
6)	Often within striking distance of the main competitors	
	Worse than competitors:	
7)	Usually marginally worse than most competitors	
8)	Usually worse than most competitors;	
9)	Consistently worse than most competitors?	

APPENDIX D

Internal Requirements/Capability Analysis

a) **THE COST EFFECTIVE CUSTOMIZATION ABILITY OF THE COMPANY AS COMPARE TO MARKET AND COMPETITORS**:

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

b) DIFFERENCIATION/PROCESS FLEXIBILITY

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

c) TIME TO MARKET

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

d) FAST RESPONSE

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

e) AFTER SALE SERVICE

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

f) PART COUNT REDUCTION

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

g) IMPROVED PRODUCTION

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

h) LOW VOLUME PRODUCTION

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

i) LOW INVENTORY

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

j) REDUCE COST AND OPERATION LENGTH

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

k) SHORT/COMPRESSED LIFE CYCLE

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

l) INCREASED SYNCHRONIZATION

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

m) LOW CYCLE TIME

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

n) EASE IN INNOVATION

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

o) REDUCE COMPUTING COST

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

p) EASE OF OPERATIONS

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

q) VISUAL AID FOR TOOL MAKERS

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

r) DESIGN FREEDOM

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

s) ASSEMBLY COST

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

t) TOOLING COST

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

u) COST ASSOCIATED WITH TIME TO MARKET

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

v) REDESIGNING COST

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

w) COST OF WASTE

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

x) PRODUCT RETURN OR WARRANTY COST

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

y) COST ASSOCIATED WITH SUPPLY CHAIN

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

z) BETTER PRODUCT FEATURES/DESIGN

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

aa) BETTER PRODUCT PERFORMANCE

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

bb) RAPID NEW PRODUCT INTRODUCTION

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

cc) VARIABLE ORDER SIZE

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

dd) QUICK DESIGN MODIFICATIONS

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

ee) SET UP TIME

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

ff) LOW DIRECT LABOR

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

gg) PRODUCT DEVELOPMENT CYCLE

	1	2	3	4	5	6	7	8	9
Importance	❑	❑	❑	❑	❑	❑	❑	❑	❑
Performance	❑	❑	❑	❑	❑	❑	❑	❑	❑

APPENDIX E

Cover Letter for RP Equipment Information

The Engineering Manager
Company ABC.

Dear Sir/Madam

I am Dr Ilyas Mazhar from Department of Mechanical Engineering at Curtin University, Western Australia, together with a colleague of mine Associate Professor Ian Howard and my PhD student Mr Ayyaz Ahmad who is pursuing for a PhD degree in Manufacturing Engineering at Curtin University Australia, are working on a research in developing a comprehensive framework for the selection and adoption of the rapid prototyping (RP) technology. The intended research would be able to provide the complete adoption solution from strategic to operational level, to ensure that the selected technology effectively manifests itself into the business operations. We hope you can assist us by providing the feedback so that the research can be completed.

Despite of all the enormous rewards offered by the RP technology, there is still a considerable hesitation in pursuing this technology by the industry particularly at Small to Medium Entrepreneurs (SME's) level. There are several reasons for this but the most important is the unavailability of a systems approach to investigate and compare the available rapid prototyping systems. Therefore, it becomes almost impossible to visualise/anticipate the potential benefits of this technology. The problem gets worsened due to the lack of knowledge and awareness of the technology under consideration. A recent observation is the unhappiness of companies those tried the technology. Again, the problem is not the technology but the lack of proper understanding of several competing/conflicting decisive factors those must be considered during the decision making and procurement procedure, which were basically ignored.

A vital part of this research is the development of an Decision Support System by considering several important factors which are not included in previous researches, which will help the practitioners in the selection of process& equipment which suits their requirements. The issues and challenges of the SME's have given a special consideration in the system design. The study requires detailed information regarding the capabilities and scope of the existing rapid prototyping equipment.

As some of the information is not available on your website, it would be appreciated if you could return the completed questionnaire in the self-addressed envelope. Should you have any questions or need more information please feel free to contact Ayyaz Ahmad via his email at ayyaz.ahmad@postgrad.curtin.edu.au .
Please let us know if you are interested to access to our Decision Support System or would like to see the results of this research.

Thank very much for your time and consideration.

Yours sincerely

Dr Muhammad Ilyas Mazhar
Lecturer
Department of Mechanical Engineering
Curtin University
Australia

APPENDIX F

Equipment Evaluation Questionnaire

Instructions:

a) Please check the appropriate box.

b) All prices mentioned are in US Dollar.

c) Multiple copies can be made in case of greater numbers of equipment.

a) **Select the equipment (**Double click the box for Check or Uncheck option)

☐ KATANA

b) Cost of the Equipment

☐ \$1000-\$5000 ☐ \$5000-\$10000 ☐ \$10000-\$20000 **Other\$**Click here to enter text.

c) Estimated Material Cost for part development

☐ \$3-\$5/inch^3 ☐ \$6-\$8/inch^3 ☐ \$9-\$11/inch^3

☐ \$12-\$13/ inch^3**Other**Click here to enter text.

d) Estimated maintenance cost /year (Describe in % of purchase price or any other parameter used by Company) Click here to enter text.

e) Possible Surface Finish

☐ ± 25µm ☐ ± 50µm ☐ ± 75µm **Other**Click here to enter text.

f) Accuracy (mm)

☐ 0.01-0.05 ☐ 0.051-0.08 ☐ 0.081-0.10 **Other**Click here to enter text.

g) Tolerance (in)

☐0.001 ☐ 0.003 ☐ 0.005 **Other**Click here to enter text.

h) Suitability of Equipment (Applications) please check the appropriate number

POOR	FAIR	GOOD	VERY GOOD	EXCELLENT	
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1	Form/Fit Analysis
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1	Functional Prototyping
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1	Rapid Tooling
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1	End Product/RM

APPENDIX G

LOCAL MATERIAL MANUFACTUERING							9/12/2005
SR. #	DESCRIPTION	UNIT	QTY 1	QTY 20	SHRTG	RATE Rs.	AMOUNT Rs.
1	ALUMINUM CHANEL 1" X 1 3/4"	RFT	24	480	480	29	13,920
2	ALUMINUM PROFILE	RFT	21.5	***860***	***860***	***74***	***63,640***
3	CUTTING DISC 14"X1/8"	NOS	0.25	5	5	90	450
4	DOOR GASKET 38"	NOS	2	40	40	29	1,160
5	DOOR GASKET 82"	NOS	2	40	40	65	2,600
6	DOOR LOCK	NOS	1	20	20	1,450	29,000
7	H H GLOVE	PAIR	2	40	40	22	880
8	HINGE 4" S S (KGI)	NOS	4	80	80	95	7,600
9	KNIFE BLADE	NOS	5	100	100	3	300
10	M/C SCREW 1" X 1/4"	NOS	32	640	640	1	416
11	M S ANGLE 1.5" X 1.5" X 3/16"	KGS	14.75	295	295	35	10,325
12	M S ANGLE 1.25" X 1.25" X 3/16"	KGS	1	20	20	35	700
13	M S PUTTY 2.5" X 3/16"	KGS	19.5	390	390	36	14,040
14	P V C TAPE 2"	ROLL	3	60	60	25	1,500
15	PLASTIC CHORD	KGS	0.6	12	12	50	600
16	POP RIVET 3.2 MM X 12.7 MM	450	65	1300	1300	0	455
17	POP RIVET 3.2 MM X 16.1 MM	463		0	0		-
18	POP RIVET 4.0 MM X 15.2 MM	560		0	0	0	-
19	POP RIVET 4.0 MM X 16.1 MM	563	80	1600	1600	0	640
20	POP RIVET 4.0 MM X 12.7 MM	550		0	0		-
21	PVC PIPE 1.5" DIA	KGS		100	100	100	
22	Jubly clump 2" Dia	NOS		24	24	10	
	AMOUNT REQUIRED						**148,226**

LOCAL MATERIAL INSTALLTION & PRODUCTION								9/12/2005
el				3X4				
Sr #	DESCRIPTION	UNIT	3X4 PAK	QTY 20	TOTAL REQ	SHOTGE	RATE RS	AMOUNT RS.
1	CAM LOCK STOPPER	NOS	45	900	900	900	1	900
2	BASE FRAME 3X3X2.6X4"	SET	0	0	-	-		-
3	BASE FRAME 3X4X2.6X4"	SET	0	0	-	-		-
4	BASE FRAME 3X4X2.67X5"	SET	1	20	20	20		-
5	BASE FRAME 2X2X2.67X4"	SET	0	0	-	-		
6	BASE FRAME 4X4X2.67X4"	SET	0	0	-	-		
7	BASE FRAME 4X5.6X2.87X4"	SET	0	0	-	-		
8	BASE FRAME 4X5.6X2.87X6"	SET	0	0	-	-		-
9	HILTY BOLT 12 MM	NOS	6	120	120	120	25	3,000
10	HILTY BOLT CHEMICAL	TUB	6	120	120	120		-
11	NUT & BOLT 1/4" X 2"	NOS	28	560	560	560	2	1,120
12	NUT & BOLT 6 MM X 90 MM	NOS	55	1100	1,100	1,100	3	2,750
13	MASKING TAPE 1"	ROLL	22	440	440	440	17	7,480
14	NUT & BOLT 3/8" x 1.5" G I	NOS	90	1800	1,800	1,800	2	3,600
15	POP RIVET 4.8 MMX 7.4 MM	NOS	1500	30000	30,000	30,000	0.40	12,000
16	SAMAD BOND (76)	QTR	1	20	20	20	105	2,100
17	SAMAD BOND	GLN	1	20	20	20	130	2,600
18	SILICONE TUBE WHITE	NOS	40	800	800	800	104	83,200
19	VINYLETILES	NOS	140	2800	2,800	2,800	26	72,800
20	ANTI STATIC	NOS		0	-	-	106	-
21	PLY WOOD	SFT	130	2600	2,600	2,600	28	72,800
	PLY WOOD 1/2"	SFT	100	2000	2,000	2,000	22	44,000
22	WOOD PARTAL	CFT	0.9	18	18	18	600	10,800
23	CAM LOCK	SET	45	900	900	900	85	76,500
24	CORRUGATED SHEET	ROLL	3	60	60	60	185	11,100
25	GAS B 141	KGS	16.52	330.4	330	330	135	44,604
26	METHLENE CHLORIDE	LTR	5.75	115	115	115	71	8,165
27	POLYOL	KGS	64.9	1298	1,298	1,298	144	186,912
28	ISOCYNATE	KGS	89	1780	1,780	1,780		
29	WAX MENSSION	KGS	3.9	78	78	78	210	16,380
30	WELDING ROD #10	PKT	0.22	4.4	4	4	200	880
31	M S ANGLE 1" X 1/8"	KGS	75	1500	1,500	1,500	38	57,000
32	M S ANGLE 1.5" X 3/16"	KGS	9.6	192	192	192	38	7,296
33	M S ANGLE 2" X 1/4"	KGS	20.15	403	403	403	38	15,314
34	M S PIPE 1.5" X 1/2"	RFT	14	280	280	280	15	4,200
35	M S PLATE 6" X 6" X 3/16	KGS	1.2	24	24	24	44	1,056
36	M S PUTTY 0.5" X 1/8"	KGS	0.28	5.6	6	6	44	246
37	M S PUTTY 1.5" X 1/4"	KGS	7.2	144	144	144	44	6,336
						-		
	TOTAL AMOUNT							755,139

SHELTER 5.6 X 4 X 2.8 M RETICULATION

4.14 X 5.74						38695								
2.24 x 2.24														
3 x 4 x 2.6														
4.14 x 4.14														
Electrical Items	**Units**	**Total**	**Store**	**Short**	**Rate Rs.**	**Amount Rs.**	**4.14 x 5.74 Qty 1**	**TO MAKE Qty 0**	**2.24 x 2.24 Qty 1**	**TO MAKE Qty 0**	**3 x 4 Qty 1**	**TO MAKE Qty 0**	**4.14 x 4.14 Qty 1**	**TO MAKE Qty 0**
A/C Distribution Box	Nos	0		0	34,000	-	1	0	1	0	1	0	1	0
A/C Microprocessor Sequencer	Nos	0		0	10,900	-	1	0	1	0	1	0	1	0
Air Con. 1 ton (Waves)	Nos	0		0	16,500	-	0	0	2	0	0	0	0	0
Air Con. 2.5 ton (Waves)	Nos	0		0	49,900	-	0		0		0	0	2	0
Air Con. 2.5 ton (Waves)	Nos	0		0	49,900	-	4	0	0	0	0	0	0	0
Air Con. 2 ton (Waves) Reversable	Nos	0		0	33,400	-	0	0	0	0	2	0	0	0
Branch Conductor	Nos	0		0	35	-	3	0	3	0	30	0	30	0
Buss Bar 3" WIDTH X 16" LONG	Nos	0		0	1,000	-	3	0	2	0	3	0	3	0
CABLE FOR BUSS BAR EARTHING 16MM DIA(Yellow/Green)	Ft.	0		0	19	-	4	0	4	0	4	0	4	0
Cable Lader As per Drawing With Supports And Accessories	Set	0		0		-	1	0	1	0	1	0	1	0
Cable lugs 'o' type close end thimble 3 mm	Nos	0		0	5	-	0	0	0	0	0	0	0	0
Cable Lugs pin type 4mm	Nos	0		0	2	-	20	0	15	0	20	0	20	0
Cable Lugs pin type thimble 2.5mm	Nos	0		0	1	-	25	0	25	0	20	0	20	0
Cable tie as per sample	Nos	0		0	0	-	30	0	25	0	15	0	15	0
Earthing Cable 40 mm/35mm square (yellow/Green)	Mtr.	0		0	110	-				0		0		0
Earthing Cable 50 mm square (yellow/Green)	Mtr.	0		0	130	-	20		16		20	0	20	0
Electric Cable 3/29 (3 Core,Red, Black, Green)	Mtr.	0		0	21	-	90	0	50	0	90	0	90	0
Electric Cable 7/44 (3 Core,Red, Black, Green)	Mtr.	0		0	53	-	35	0	25	0	35	0	35	0
Electric Cable 110/76 (3 Core,Red, Black, Green)	Mtr.	0		0	35	-	35	0	25	0	35	0	35	0
Electric tape	Nos	0		0	11	-	2	0	2	0	2	0	2	0
Fire Extinguisher ABC 4 KG		0		0	800	-	0		1	0		0		0
Fire Extinguisher ABC 6 KG	Nos	0		0	1,500	-	1	0	0	0		0		0
Fire Extinguisher (CO2) 5 KG	Nos	0		0	2,750	-	0	0	0	0	1	0	1	0
Galvanized out door plateform	Nos	0		0	1,350	-	4	0	2	0	2	0	2	0
Nut And Bolts with washers 8mm & 10 mm	Nos	0		0	3	-	8	0	8	0	8	0	8	0
ON-OFF DOUBLE BUTTON Switch (CLIPSEL)	Nos	0		0	94	-	1	0	1	0	1	0	1	0
Outdoor light 60 W	Nos	0		0	350	-	1	0	1	0	1	0	1	0
Power Plug For Ac	Nos	0		0	210	-	4	0	2	0	2	0	2	0
Roxtec Complus 6x2 double Frame 18x2 port	Nos	0		0		-	2	0	0	0	1	0	1	0
Roxtec Comlite 6x18 S Frame 18x2 port	Nos	0		0		-	0	0	1	0	0	0	0	0
Roxtec RS 50 AISI 316 Round Seal With Flange	Nos	0		0		-	1	0	0	0	1	0	1	0
Self taping screws #10	Nos	0		0	1	-	35	0	35	0	20	0	20	0
Socket Three Pin (ZIB)	Nos	0		0	94	-	2	0	2	0	6	0	6	0
Thimble (As per earthing Wire Dia) (8 & 10 mm)	Nos	0		0	5	-	8	0	8	0	8	0	8	0
Three pin Socket Round Shape	Nos	0		0	40	-	2	0	2	0	2	0	2	0
Trunking 100 x 25 mm / 60 X 60	Mtr.	0		0	147	-	30	0	6	0	28	0	28	0
Trunking 60 x 25 mm / 40 x 40	Mtr.	0		0	150	-	28	0	15	0	26	0	26	0
Trunking 25 x 25 mm	Mtr.	0		0	137	-	32	0	12	0	30	0	30	0
Trunking 40 x 25 mm / 33 X 33	Mtr.	0		0	65	-	14	0	15	0	12	0	12	0
Tube Lights (single) (Sogo)	Nos	0		0	390	-	4	0	0	0	4	0	4	0
Tube Lights (Double) (Sogo)	Nos	0		0	390	-	0	0	1	0	0	0	0	0
Copper Strip	Mtr.	0		0	270	-	22	0	10	0	18	0	18	0
TOTAL RS.						-								

BOQ FOR SHELTER PROJECT

38695

Electric Items	Units	Store	Type A 1	Type C 1	Type D 1	Qty	Qty	Qty	Total Qty	SHORT	Rate Rs.	Amount Rs.
EARTHING CABLE 16MM DIA(Yellow/Green)	Mtr.		6	2	3	-	-	-	-	0	**58**	**-**
EARTHING CABLE 35MM DIA(Yellow/Green)	Mtr.		35	50	80	-	-	-	-	0	**130**	**-**
A/C Distribution Box	Nos		1	1	1	-	-	-	-	0	30,000	-
Buss Bar 3" WIDTH X 16" LONG	Nos		2	1	2	-	-	-	-	0	1,000	-
Buss Bar 3" WIDTH X 8" LONG	Nos		2	1	6	-	-	-	-	0	600	-
Cable Lader As per Drawing With Supports And Accessories	Set		1	1	1	-	-	-	-	0		-
Cable Lugs 2.5mm	Nos		20	15	15	-	-	-	-	0	1	-
Cable Lugs 4mm	Nos		10	10	15	-	-	-	-	0	2	-
Cable Tie 10"	Nos		100	100	125	-	-	-	-	0	1	-
Cable Tie 4"	Nos		15	15	15	-	-	-	-	0	1	-
Copper C-clamps	Nos		18	22	35	-	-	-	-	0	32	-
Copper Strip 1" x 2mm	Mtr.		17	15	22	-	-	-	-	0	270	-
Electric Cable 3/29 (3 Core,Red, Black, Green)	Mtr.		35	35	30	-	-	-	-	0	20	-
Electric Cable 7/44 (3 Core,Red, Black, Green)	Mtr.		0	0	0	-	-	-	-	0	52	-
Electric tape	Nos		2	2	2	-	-	-	-	0	10	-
Electric tape Green	Nos		2	2	1	-	-	-	-	0	10	-
Flexible Pipe 0.5" Dia	Mtr.			1	1		-	-				
Galvanized out door plateform	Nos		2			-	-	-	-	0		-
Magnetic Door lock contact alarm wired to DDF panel	Nos		1	1	1	-	-	-	-	0	350	-
Nut And Bolts with washers 1/4" X 3/4"	Nos		36	36	12	-	-	-	-	0	2	-
ON-OFF DOUBLE BUTTON Switch (CLIPSEL)	Nos		1	1	1	-	-	-	-	0	65	-
Pakistan Cable 1mm Black	Mtr.			4	4		-	-				
Pakistan Cable 1mm Red	Mtr.			4	4		-	-				
Power Plug For Ac	Nos		2		4	-	-	-	-	0	200	-
Roxtec Complus 6x2 double Frame 18x2 port with FRP Frame	Nos		1	1	2	-	-	-	-	0		-
Self taping screws 10 #, 2"	Nos		25	25	35	-	-	-	-	0	0	-
Self Taping Screws 14 # , 1"	Nos		20	15	30	-	-	-	-	0	1	-
Self Taping Screws 14#, 2"	Nos		8	8	10	-	-	-	-	0	1	-
Shroud for 35 mm sq Green Color	Nos			30	50		-	-				
Socket Three Pin (ZIB)	Nos		2	2	2	-	-	-	-	0	96	-
Thimble 10 mm	Nos		15	20	20	-	-	-	-	0	5	-
Thimble 8 mm	Nos		20	35	50	-	-	-	-	0	5	-
Three pin Socket Round Shape	Nos		2	2	2	-	-	-	-	0	40	-
Trunking (25 X 25)	Mtr.		20	18	22	-	-	-	-	0	46	-
Trunking (60 x 60)	Mtr.		0	3	3	-	-	-	-	0	147	-
Tube Lights (double) (Sogo)	Nos		2	3	4	-	-	-	-	0	400	-
TOTAL												**-**

APPENDIX H

Rating Scales

Wax (L: .092)

Intensity Name	Priority
Yes	.800
Partial with Limitations	.200
No	.030

Metal/Stainless steel/Titanium/Cobalt Chrome (L: .020)

Intensity Name	Priority
Yes	.800
Partial with Limitations	.200
No	.030

Plastic/ABS (L: .562)

Intensity Name	Priority
Yes	.800
Partial with Limitations	.200
No	.030

Functional/Form Fit Analysis (L: .363)

Intensity Name	Priority
Excellent	.990
Very Good	.800
Good	.600
Fair	.400
Poor	.200

Rapid / DirectTooling (L: .046)

Intensity Name	Priority
Excellent	.990
Very Good	.800
Good	.600
Fair	.400
Poor	.200

End Product/RM (L: .045)

Intensity Name	Priority
Excellent	.990
Very Good	.800
Good	.600
Fair	.400
Poor	.200

Visualisation/Conceptual Design (L: .430)

Intensity Name	Priority
Excellent	.990
Very Good	.800
Good	.600
Fair	.400
Poor	.200

Step Function Scales

Complex curves (L: .655)

Intensity Name	Step LB
Excellent	1
Very Good	1.99
Good	2
Average	3

Undercuts (L: .345)

Intensity Name	Step LB
Excellent	1
Very Good	1.99
Good	2
Average	3

Build Size (L: .176)

Intensity Name	Step LB
Very Low	0
Low	15
Medium	29
High	45
Very High	100

Equipment cost (L: .713)

Intensity Name	Step LB
Very Cheap	0
Cheap	15000
Average	30000
Moderate	45000
Expensive	80000
Very Expensive	1000000

AID	Alternative	Total	MATERIAL CHOICE Photosilver/Ceramic powder (L: .022)
A1	**CNC/Rapid Tooling**	.0029	No
A5	Service Bureau	.0148	Yes
A6	**RP/RM- VFLASH(3D)**	.0025	No
A7	RP/RM- PROJET 3000 (3D)	.0141	No
A8	RP/RM- PROJET IPROMP 8000	.0131	No
A9	RP/RM- PROJETHD 5000 (3D)	.0134	No
A10	RP/RM-VIPER SLA (3D)	.0131	No
A11	RP/RM-IPRO 9000 XL SLA (3D)	.0135	No
A12	RP/RM HIQ SLS (3D)	.0000	
A13	RP/RM-SPRO 230 SLS (3D)	.0132	No
A14	RP/RM-CPX3000 (3D)	.0130	No
A15	RP/RM- RM 3000 (CMET)	.0147	No
A16	RP/RM- RM 6000II (CMET)	.0131	No
A17	RP/RM-AUREUS (Envision TEC)	.0149	No
A18	RP/RM- PIXCERA (Envision TEC)	.0140	No
A19	RP/RM- DDSP(Envision TEC)	.0000	
A20	RP/RM-PREFACTORY DSP (Envision TEC)	.0159	Yes
A21	RP/RM- PREFACTORY XTREME(Envision	.0152	No
A22	RP/RM D76+ (Solidscape)	.0123	No
A23	RP/RM- R66+ (Soliscape)	.0132	No
A24	RP/RM-T612BT (Solidscape)	.0125	No
A25	RP/RM- SD 300 (Cubic)	.0152	No
A26	RP/RM-SLM 100 (Realizer)	.0118	Yes
A27	RP/RM- SLM 50 (Realizer)	.0120	No
A28	RP/RM- SLM 250 (Realizer)	.0121	Yes
A29	RP/RM- FORMIGA P100 (EOS)	.0114	No
A30	RP/RM-EOSINT P395/390 (EOS)	.0117	No
A31	RP/RM- EOSINT M 270/280 upgrade	.0116	No
A32	RP/RM- FORTRUS 360 mc (Stratasys)	.0135	No
A33	RP/RM- FORTRUS 400 mc (Stratasys)	.0136	No
A34	RP/RM- FORTRUS 900 mc (Stratasys)	.0140	No
A35	RP/RM- DIMENSION ELITE (Stratasys)	.0165	No
A36	RP/RM- DIMENSION UPRINT (Stratasys)	.0166	No

	Distributive mode		RATINGS
AID	**Alternative**	**Total**	**MATERIAL CHOICE Photosilver/Ceramic powder (L: .022)**
A78	RP/RM PROJET1000/1500	.0160	No
A79	N/A	.0000	
A80	RP/RM- D66+ (Solidscape)	.0113	No
A81	RP/RM-T76+ (Solidscape)	.0122	No
A82	RP/RM MOJO 3D (Stratasys)	.0159	No
A83	RP/RM- CONNEX 260 (Objet)	.0134	No
A84	RP/RM- CONNEX 350 (Objet)	.0134	No
A85	RP/RM- OBJET 24 (Objet)	.0164	No
A86	RP/RM- OBJET 30 Pro (Objet)	.0164	No
A87	RP/RM- EDEN 250 (Objet)	.0143	No
A88	RP/RM- EDEN 350/350 V (Objet)	.0134	No
A89	**RP/RM-Z printer 150 (Z Corp)**	.0023	No
A90	RP/RM-Z printer 250 (Z Corp)	.0161	No
A91	**RP/RM- Z printer 350 (Z corp)**	.0022	No
A92	RP/RM- Z printer 450 (Z corp)	.0137	No
A93	RP/RM- M1 CUSING (Concept Laser)	.0118	No
A94	RP/RM- M2 CUSING (Concept Laser)	.0116	No
A95	RP/RM- M3 LINEAR (Concept Laser)	.0118	No
A96	RP/RM- MLAB CUSING (Concept Laser)	.0120	No

	Distributive mode		STEP
AID	**Alternative**	**Total**	**PRODUCT PROFILE** **Complexity** **Complex curves** **(L: .655)**
A1	**CNC/Rapid Tooling**	.0029	1
A5	Service Bureau	.0148	1
A6	**RP/RM- VFLASH(3D)**	.0025	1
A7	RP/RM- PROJET 3000 (3D)	.0141	1
A8	RP/RM- PROJET IPROMP 8000	.0131	1
A9	RP/RM- PROJETHD 5000 (3D)	.0134	1
A10	RP/RM-VIPER SLA (3D)	.0131	1
A11	RP/RM-IPRO 9000 XL SLA (3D)	.0135	1
A12	RP/RM HIQ SLS (3D)	.0000	
A13	RP/RM-SPRO 230 SLS (3D)	.0132	2
A14	RP/RM-CPX3000 (3D)	.0130	1
A15	RP/RM- RM 3000 (CMET)	.0147	1
A16	RP/RM- RM 6000II (CMET)	.0131	1
A17	RP/RM-AUREUS (Envision TEC)	.0149	1
A18	RP/RM- PIXCERA (Envision TEC)	.0140	1
A19	RP/RM- DDSP(Envision TEC)	.0000	
A20	RP/RM-PREFACTORY DSP (Envision TEC)	.0159	1
A21	RP/RM- PREFACTORY XTREME(Envision	.0152	1
A22	RP/RM D76+ (Solidscape)	.0123	1
A23	RP/RM- R66+ (Soliscape)	.0132	1
A24	RP/RM-T612BT (Solidscape)	.0125	1
A25	RP/RM- SD 300 (Cubic)	.0152	2
A26	RP/RM-SLM 100 (Realizer)	.0118	1.99
A27	RP/RM- SLM 50 (Realizer)	.0120	1
A28	RP/RM- SLM 250 (Realizer)	.0121	1.99
A29	RP/RM- FORMIGA P100 (EOS)	.0114	1.99
A30	RP/RM-EOSINT P395/390 (EOS)	.0117	1.99
A31	RP/RM- EOSINT M 270/280 upgrade	.0116	1.99
A32	RP/RM- FORTRUS 360 mc (Stratasys)	.0135	1.99
A33	RP/RM- FORTRUS 400 mc (Stratasys)	.0136	1.99
A34	RP/RM- FORTRUS 900 mc (Stratasys)	.0140	1.99
A35	RP/RM- DIMENSION ELITE (Stratasys)	.0165	1.99
A36	RP/RM- DIMENSION UPPRINT (Stratasys)	.0166	1.99

A41	**RP/RM- z PRINTER 310 PLUS (Z**	.0023	1
A42	RP/RM- Z Corp Ultra (Z Corp)	.0119	1
A43	RP/RM- KATANA (Kira Corp.)	.0127	3
A44	RP/RM- SCS-1000 HD (DMEC)	.0022	
A45	RP/RM- SCS-9000 (DMEC)	.0087	1
A46	RP/RM- ACCULAS SI-C1000 (DMEC)	.0000	
A47	RP/RM- MTT SLM 125 (MTT)	.0005	
A48	RP/RM- MTT SLM 250 (MTT)	.0007	
A49	RP/RM- RS-6000 (Shanghai UT)	.0073	1
A50	RP/RM- RS-3500 (Shanghai UT)	.0071	1
A51	**RP/RM- HRP-IIIA LOM (Wuhan**	.0020	3
A52	RP/RM- HRPS-IV SLS(Wuhan Binhu)	.0098	2
A53	RP/RM- HRPL-III SLA (Wuhan Binhu)	.0123	1
A54	RP/RM- ZORRO (Sintermask)	.0098	1.99
A55	RP/RM- PM 100T SLS (Phenix)	.0103	1.99
A56	RP/RM- PXL (Phenix)	.0107	1.99
A57	RP/RM- PXS (Phenix)	.0105	1.99
A58	RP/RM- PXS DENTAL (Phenix)	.0102	1
A59	RP/RM- HTS 300 (Fochif Tech)	.0162	
A60	RP/RM- HTS 400 (Fochif Tech)	.0156	
A61	**RP/RM-Inspire S200 (Beijing**	.0025	1.99
A62	RP/RM-Inspire s250 (Beijing Tiertime)	.0169	1.99
A63	RP/RM- ARCAM A2 (Arcam)	.0000	
A64	RP/RM- ARCAM A1 (Arcam)	.0000	
A65	RP/RM- FCUBIC C300 (Fcubic)	.0000	
A66	RP/RM- FCUBIC C50 (Fcubic)	.0000	
A67	RP/RM-Inspire D255(Beijing Tiertime)	.0002	
A68	RP/RM-Inspire D290(Beijing Tiertime)	.0162	1.99
A69	RP/RM-Inspire A370 (Beijing Tiertime)	.0000	
A70	RP/RM-Inspire A450 (Beijing Tiretime)	.0142	1.99
A71	**RP/RM-FREE FORM PICO (ASIGA)**	.0023	2
A72	RP/RM- FREE FORM PICO PLUS 27	.0157	2
A73	RP/RM - FREE FORM PICO PLUS 33	.0157	2
A74	RP/RM- FREE FORM PICO PLUS 39	.0157	2
A75	RP/RM- HP Designer Jet (HP)	.0158	2
A76	RP/RM- HP Designer Jet Color (HP)	.0158	2
A77	RP/RM- Matrix 300 (MCOR)	.0153	2

	Distributive mode		STEP
AID	**Alternative**	**Total**	**PRODUCT PROFILE** **Complexity** **Complex curves** **(L: .655)**
A78	RP/RM PROJET1000/1500	.0160	1
A79	N/A	.0000	
A80	RP/RM- D66+ (Solidscape)	.0113	1
A81	RP/RM-T76+ (Solidscape)	.0122	1
A82	RP/RM MOJO 3D (Stratasys)	.0159	1.99
A83	RP/RM- CONNEX 260 (Objet)	.0134	1
A84	RP/RM- CONNEX 350 (Objet)	.0134	1
A85	RP/RM- OBJET 24 (Objet)	.0164	1
A86	RP/RM- OBJET 30 Pro (Objet)	.0164	1
A87	RP/RM- EDEN 250 (Objet)	.0143	1
A88	RP/RM- EDEN 350/350 V (Objet)	.0134	1
A89	**RP/RM-Z printer 150 (Z Corp)**	.0023	1
A90	RP/RM-Z printer 250 (Z Corp)	.0161	1
A91	**RP/RM- Z printer 350 (Z corp)**	.0022	1
A92	RP/RM- Z printer 450 (Z corp)	.0137	1
A93	RP/RM- M1 CUSING (Concept Laser)	.0118	1.99
A94	RP/RM- M2 CUSING (Concept Laser)	.0116	1.99
A95	RP/RM- M3 LINEAR (Concept Laser)	.0118	1.99
A96	RP/RM- MLAB CUSING (Concept Laser)	.0120	1

Compare the relative importance with respect to: Composite/Thermoplastic (L: .022)

Circle one number per row below using the scale:
1 = Equal 3 = Moderate 5 = Strong 7 = Very strong 9 = Extreme

1	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CNC/Rapid Tooling
2	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- VFLASH (3D)
3	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- CONNEX 50(
4	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
5	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
6	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
7	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM F
8	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
9	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
10	CNC/Rapid Tooling	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- VFLASH (3D)
11	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- CONNEX 50(
12	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
13	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
14	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
15	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM F
16	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
17	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
18	RP/RM- VFLASH (3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	RP/RM- CONNEX 50(
19	RP/RM- VFLASH (3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
20	RP/RM- VFLASH (3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
21	RP/RM- VFLASH (3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
22	RP/RM- VFLASH (3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM F
23	RP/RM- VFLASH (3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
24	RP/RM- VFLASH (3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
25	RP/RM- CONNEX 50(	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
26	RP/RM- CONNEX 50(	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
27	RP/RM- CONNEX 50(	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
28	RP/RM- CONNEX 50(	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM F
29	RP/RM- CONNEX 50(	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
30	RP/RM- CONNEX 50(	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
31	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
32	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
33	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM F
34	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
35	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
36	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
37	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM F
38	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
39	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
40	RP/RM-Inspire S200	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM-FREE FORM F
41	RP/RM-Inspire S200	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
42	RP/RM-Inspire S200	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
43	RP/RM-FREE FORM F	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	RP/RM-Z printer 150
44	RP/RM-FREE FORM F	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(
45	RP/RM-Z printer 150	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM- Z printer 35(

Compare the relative importance with respect to: Complex curves (L: .655)

Circle one number per row below using the scale:
1 = Equal 3 = Moderate 5 = Strong 7 = Very strong 9 = Extreme

1	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CNC/Rapid Tooling
2	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- VFLASH(3D)
3	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- CONNEX 500
4	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
5	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
6	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
7	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM P
8	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
9	IDEAL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
10	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM- VFLASH(3D)
11	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- CONNEX 500
12	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
13	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
14	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
15	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM P
16	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
17	CNC/Rapid Tooling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
18	RP/RM- VFLASH(3D)	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM- CONNEX 500
19	RP/RM- VFLASH(3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
20	RP/RM- VFLASH(3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
21	RP/RM- VFLASH(3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
22	RP/RM- VFLASH(3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM P
23	RP/RM- VFLASH(3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
24	RP/RM- VFLASH(3D)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
25	RP/RM- CONNEX 500	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM- z PRINTER 3
26	RP/RM- CONNEX 500	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
27	RP/RM- CONNEX 500	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
28	RP/RM- CONNEX 500	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM P
29	RP/RM- CONNEX 500	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
30	RP/RM- CONNEX 500	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
31	RP/RM- z PRINTER 3	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	RP/RM- HRP-IIIA LO
32	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Inspire S200
33	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM P
34	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
35	RP/RM- z PRINTER 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
36	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	RP/RM-Inspire S200
37	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-FREE FORM P
38	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
39	RP/RM- HRP-IIIA LO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
40	RP/RM-Inspire S200	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM-FREE FORM P
41	RP/RM-Inspire S200	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM-Z printer 150
42	RP/RM-Inspire S200	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
43	RP/RM-FREE FORM P	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	RP/RM-Z printer 150
44	RP/RM-FREE FORM P	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RP/RM- Z printer 350
45	RP/RM-Z printer 150	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RP/RM- Z printer 350