Development of Agility Enhancement Strategies for Agile Manufacturing

THESIS

Submitted in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

Pavan Kumar Potdar

Under the supervision of

Prof. Srikanta Routroy

BITS Pilani
Pilani | Dubai | Goa | Hyderabad

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE
PILANI – 333 031 (RAJASTHAN) INDIA

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CERTIFICATE

This is to certify that the thesis entitled "**Development of Agility Enhancement Strategies for Agile Manufacturing**" which is submitted for the award of Ph.D degree of the institute, embodies original work done by **Pavan Kumar Potdar**, ID.No. **2009PHXF431P** under my supervision.

Signature in full of the Supervisor ________________

Name : **Dr. Srikanta Routroy**

Designation: **Associate Professor**
Mechanical Engineering Department
BITS-Pilani, Pilani Campus

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Abstract

The business dynamics has changed drastically over the few decades due to persistent changes in customer requirements, frequent technological innovations, volatile market conditions, increased competition at local and global level, availability of alternate sourcing options, changes in sourcing contract from long term to short term, shrinking product life cycles etc. The earlier manufacturing strategy – mass production system relied on producing products in huge quantities and thereby maintains lower unit production cost. The success of this system was attributed to the high demand for a small set of products which the customers were forced to consume without having any alternate choice. The profit was function of volume and manufacturing scenario was very stable. With the changes in manufacturing scenario i.e. wide choice of products for consumer to choose from and innovations in technology and processes – the mass production system was found to be unviable. The volume based profit making ventures failed to sustain and manufacturing industry with this strategy started to collapse. The search for a better manufacturing philosophy which could work in a dynamic, flexible and unpredictable environment was urgently needed to revive manufacturing industry. Agile Manufacturing (AM) is proposed in response to the current business environment as a solution and is perceived as the need to address these issues. The manufacturing organizations are striving for its successful adoption in order to maintain competitive advantage in their business. AM has attracted contributions from researchers around the globe. It can be viewed as an evolution or logical progression from existing manufacturing systems.

The current research on AM is focused on developing the systematic methodologies to study and analyze the various aspects related to enhance the agility of AM in general and Indian industries in specific. The methodologies are proposed and developed to understand, analyze and select right set of Agile Manufacturing Enablers (AMEs) and Agile Manufacturing Impediments (AMIs) in a manufacturing environment so that the manufacturing organizations can be given a route-map for optimally allocating the efforts and resources for its successful implementation and agility enhancement. Multi-Criteria Decision Making (MCDM) tools have been used address these issues. The strategies and methodologies are also proposed and

developed to determine the agility level of the organizations and to carry out the performance analysis of AM implementation along the outcomes and their Key Performance Indicators (KPIs). MCDM tools like AHP/ISM/FMICMAC/ DEMATEL etc. have been used to develop these methodologies. Finally a generic benchmarking framework is proposed along with step by step implementation process to enhance the agility level on a continuous basis.

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CHAPTER 1

Thesis Overview

1.1 Backdrop of Agile Manufacturing

The business dynamics in the manufacturing environment has changed drastically over the last two decades due to rapid changes in manufacturing and information technology, changes in market conditions, increased customer requirements (i.e. quick response, lower costs, greater customization etc.), product proliferation with shorter and uncertain life cycles, intensified off-shoring and outsourcing strategies, and increased competition from local to global arena. Therefore, the survival and success of a manufacturing organization has become even more difficult. It is crucial for any manufacturing organization to deal with the changes much quickly; otherwise there is a threat to becoming extinct. Manufacturing organizations that refused to heed to the changes have shut shop. The refusal to heed to the changing scenario usually stems from the fact that the organizations presume what is their core competency will tide them over during the turbulent times. Change in technology, materials and processes sometimes render these rigid decisions as failures. Many Iron and Steel industries that did not update their technologies/ processes, had to close down as high operation costs made them commercially unviable.

Manufacturing organizations need to incorporate processes to deal with changes. There have been major shifts in the core business principles too, hitherto it was a "manufacturer centric" in nature, where the business model was simple with least number of variables and a lot of confidence about what the customer really wanted. The premise on which the business was conducted has become obsolete. The socio-economic environment in which the manufacturing companies are expected to operate now, have become unstable owing to multitude of factors viz. non-uniform local legislations, risk due to financial upheavals, paucity of resources, vacillating loyalty of customers and suppliers, and a strong emphasis on "customer desires and satisfaction". This has led to a situation where the sustainability of a manufacturing company is directly related to its ability - to face the growing competition and to operate at the lowest margins to retain customer base while operating in a hostile business environment. This had necessitated a review of existing business priorities and practices. An urgent need for a better and innovative manufacturing technique that can support the manufacturing company to operate in this hostile environment was needed. This provided the impetus to re-assess the “mission and vision statements” and strategic plans of the manufacturing organization. It was realized that only those manufacturing organizations which could identify the need for changes in business practices and be more adaptable to varying environment were most likely to prosper and sustain. Therefore, manufacturing organizations are striving to develop capabilities to adapt as per external requirements. In fact, change is a major driver that is identified for successful business (Luis *et al.*, 2009). Adaptability has also been identified as a key game-changer. Adaptability basically means that the enterprise is open to reorganize its operations in response to changes in product type, variety and technology. The concept of virtual organizations evolved out of the concept of being adaptable as not every enterprise could have the technical capability to reorganize itself rapidly. Creation of virtual enterprises based on their core-competencies, could be formed and dissolved, depending upon the requirements and thereby provide a level of adaptability (Vinod *et al.*, 2013). During the past few years, the manufacturing arena had been orienting towards the relatively new paradigm, “Agile Manufacturing” (AM) (Power *et al.*, 2001; Jin-Hai *et al.*, 2003; and Crocitto and Youssef, 2003) as the one promoting a healthy and sustainable business environment and being dexterous in meeting customer expectation in the shortest possible time. It leverages the unpredictability into business opportunities to maintain the competitive edge and sustain the business. AM being customer centric, uses the “voice” of customer during various operation phases - product design, supplier selection and process design, customized marketing strategies and allied services. The core concept of AM is built around two features - customer preferences and adaptability. Adaptability implicitly means being flexible. It is a natural evolution from the original concept of “lean manufacturing (the emphasis is on cost-cutting)” (Yusuf *et al.*, 1999). It is one of the operational strategies which organizations have adopted to address uncertainties resulting from worldwide economic recession, shortening of product life cycle, supplier constraints and obsolete technologies (Dubey and Gunasekaran, 2015).The integration of organizations, people and technology into a meaningful unit by deploying advanced information technologies and flexible organizational structures to support highly skilled, knowledgeable and motivated people is essential for AM implementation (Goldman and

Nagel, 1993; Gunasekaran, 1999). The application of agile manufacturing has the ability to boost manufacturing through simultaneous improvement in various implied objectives (cost, quality, flexibility, delivery, service and environment) and it will in turn lead to increased competitiveness (measured by indicators for labour productivity, customer loyalty, new product development success, sales volume, Return on Asset (ROA) and responsiveness to changes in competitive conditions) (Vazquez-Bustelo *et al.*, 2007). It considers agility as a key concept necessary to survive against competitors under an unpredictable turbulent and changing environment (Dowlatshahi and Cao, 2006). Agility is the ability to thrive in an environment of continuous and often unanticipated change (Sarkis, 2001).

The underpinning principles of agility comprise: delivering value to the customer; being ready for change; valuing human knowledge and skills; and forming virtual partnerships (McCurry and McIvor, 2002). It is the capability of an organization to rapidly reorganize and streamline its processes to meet the unpredictable volatile changes in markets and customer preferences. Thus, AM resolves the earlier issues faced by the manufacturing enterprises and the implementation of AM principles and practices will lead to survival and sustainability. AM relies on virtual enterprise to overcome few of the inherent competency issues and needs active participation at every level and by each partner. This necessitates transparent and quick sharing of data/information using latest information technologies (Integrated Business Information Systems), quicker decision making at all levels in the hierarchy, use of flexible tools/machinery, developing and leveraging core-competencies of partners, maintaining amicable working environment, regular training and knowledge sharing, and a good customer/supplier relationship management (Vinodh *et. al.*, 2011). The enterprises operating in stable and well defined markets too are not immune to the unpredictability and complexities in the environments. Implementation of AM principles will help the enterprises to combat these hostile factors.

1.1.1 Research Gaps Focused in the Current Thesis

In this section, the identified research gaps, their significance and the proposed solutions are briefly discussed. The literature support for the derived research gaps is contextually presented along the different chapters in the current thesis so as to comprehensively develop the discussion.

1.1.1.1 Literature review of agile manufacturing

Agile Manufacturing (AM) has evolved as a revolutionary way of manufacturing the products while managing the uncertainties, product introduction time, responsiveness, innovation, superior quality etc. along the supply chain to satisfy the ever increasing customer demand and to maximize the profit. Literature review was carried out on AM to critically analyse the literature related to various dimensions of AM and to report the findings. Three hundred scholarly articles spanning from 1993 to 2016, by various researchers and practitioners on AM collected from different sources (i.e. Google Scholar and Research Gate) with a focus to capture research contribution, research methodologies, regional importance, author profile, type of industry, and different tools, techniques and methodologies used. Followings are the findings drawn from the study:

- Research on AM is being conducted all across the globe including developed, emerging and under developed countries. However USA has outnumbered all the countries with approximately one third of the research on AM contributed from USA followed by UK, India and China.
- The benefits of AM in Indian companies have not clearly spelt out although many Indian companies have implemented it. However AM implementations in companies abroad have resulted in considerable improvements in business outcomes in terms of reduced product introduction, response and delivery times, enhanced ROA, increased market share etc.
- Academicians from various research institutes have contributed to a major portion of the research on AM than the practitioners. This could be because in industry practitioners are giving more importance on the implementation of AM rather on publication of research papers. Also many academicians are working in co-ordination with industry personnel for the implementation of AM.
- Most of the research papers are found to be either descriptive or empirical in nature. A lot of importance is being given towards the AM performance measurement and process analysis. Researchers have focused on the real time case studies in different industries to analyse the available data for deciding the future goals of the industries.
- The research on AM has picked up from the start of 21st century. Automotive and electronics product manufacturing industries has been the focus of AM implementations, but AM also has been adopted by other type of industries like Software, Textile-Clothing-Fabrics, Electrical industries and SMEs. However, the

adoption of AM in telecom industry, food industry, casting industry and service industries are not widespread due the fear of high implementation cost and uncertainty of future.

- Multi-Criteria Decision Making (MCDM) tools have been widely used by various researchers on different aspects of AM like manufacturing agility improvement, exploring relationships among various criteria, agility measurement, supplier selection etc. Although benchmarking is applied in many areas to compare and enhance the performance, but it has never been used in AM.

1.1.1.2 Agile manufacturing enablers

Agile Manufacturing Enabler (AME) is the factor that has the capability to provide or enable or enhance the level of agility in the agile manufacturing system. Many researchers have carried out research on AMEs and identified AMEs which may be specific or generic in nature. The manufacturing organization focusing on AM should identify the AMEs and then define the domain of each enabler so that right AMEs can be selected in a specific manufacturing environment. Although number of enablers have impact directly or indirectly or both ways on the agility performance of a manufacturing system, it is not possible for an organization to focus on all the enablers at a time in order to enhance agility performance level. Therefore, it is essential to identify the AM enablers which have high driving and low dependence power on the agility performance so that manufacturing companies can streamline their efforts accordingly. For analyzing and establishing the relationship between AMEs in the specific environment, the Interpretive Structural Modeling (ISM) integrated with Fuzzy Matriced Impacts Croises Multiplication Appliqueeaun Classement (FMICMAC) algorithm is proposed. The proposed methodology was applied to an Indian electrical hardware manufacturing company for analyzing the AMEs. In the case company, AMEs were leveled across five levels in five iterations using ISM. Adaptability, devolution of authority and supply chain integration are at the base of the hierarchy of structural framework. The case company should strive to acquire capability along these three AMEs which will in turn leads to agility enhancement. The AMEs (i.e. information visibility and transparency, devolution of authority and adaptability) were in driver/ independent cluster which means that these three AMEs have high influence on rest of the eight other AMEs. Therefore, these four AMEs (i.e. information visibility and transparency, devolution of authority, adaptability, and supply chain integration) were considered as the prerequisite for implementing AM in the case company. Although this result was for a case company (i.e. an Indian electrical hardware manufacturing company), the obtained results cannot be too off-mark for the manufacturing companies similar in nature. Moreover, the current study may be used as a basis to investigate more details regarding agile manufacturing in general and agile manufacturing enablers in specific.

1.1.1.3 Agile manufacturing impediments

The AM implementation process would most likely get delayed if root causes of Agile Manufacturing Impediments (AMIs) are not identified and effectively addressed. These AMIs have deep roots along various tangible and intangible issues of the organizations. Therefore, an organization needs to target the appropriate AMIs to enhance the agile development as putting efforts on all AMIs is not feasible. But many a times organizations fail to identify the appropriate AMIs due to improper analysis. Thus, considering all the aforementioned issues, this study proposed an approach to identify the appropriate impediments for monitoring the smooth implementation of AM in specific environment. Investigation of these AMIs is necessary to understand and subjugate them. From our extensive literature review, it is observed that a few research have been carried on AMIs related to its identification and contextual relationship (Kamarulzaman *et al.*, 2015; Patil, 2015; Singh *et al.,* 2013; Hasan *et al.*, 2007). Current work proposes two methods to analyze the AMIs. The first method uses Fuzzy Decision-Making Trail and Evaluation Laboratory (DEMATEL) to identify the AMIs based on cause and effect grouping and the influence of impediments on other impediments to estimate the criteria weights. The proposed methodology is applied to an Indian Automobile manufacturing company to understand the salient features of the concept. The second method uses ISM – FMICMAC method to identify the right set of significant categories of AMIs on which an organization should initiate action to enhance its performance. It is essential that the appropriate set of significant categories of AMIs should be identified to enhance the agile development in the organization. But many a times organizations fail to identify these appropriate set of significant categories of AMIs due to improper analysis. Thus, this approach has been proposed for monitoring the smooth implementation of AM in a specific environment.

1.1.1.4 Measurement of agility

Agile manufacturing has emerged as the paradigm to survive in the difficult operating environments possessing characteristics of flexibility and responsiveness. Many methods for measuring manufacturing agility have been proposed and reported in literature. Considering the research in the field of measuring agility, two pertinent questions emerge:

- While deciding the weights of the enablers, shouldn't the enablers be compared to provide more information regarding their importance? Also, previous studies do not evaluate the consistency of these ratings?
- Previous studies do not provide information regarding the evolution of agility in the enterprise. How was the agility of the enterprise in the past? How is it in the present? How will it be in the future?

A methodology is proposed for measuring agility of the manufacturing system to answer these two questions. The proposed methodology combines the fuzzy Analytic Hierarchy Process (AHP) for determining the fuzzy synthetic extents (FSEs) of the weights of the AMEs and the triangular fuzzy numbers (TFNs) used for capturing the average performance ratings of AMEs. The performance of the AMEs is judged at three intervals of time which are represented as past performance, present performance and future expectation. The fuzzy synthetic extent of the weights of the AMEs and the average fuzzy performance ratings for the performance ratings of the AMEs at each interval of time are combined to determine the Fuzzy Agile Manufacturing Index (FAMI) for the respective time period. Then the Euclidean distance to the nearest predetermined agility level is calculated to determine the performance of the organization along the agile dimension at the specified intervals of time. The applications of fuzzy AHP as a multi criteria decision making tool are well known. Since the proposed methodology uses fuzzy AHP and combines them with the average performance ratings of the AME's to calculate the FAMI, this method is easy to use by industry experts as well as academics alike and does not require sophisticated tools for its deployment. Also, in case of a change in AMEs due to potential environmental changes, the proposed model can effectively calculate the manufacturing agility along the new AMEs with the expert opinion regarding the importance weights and performance of the new AMEs forming the input to the model. The combination of such characteristics makes the methodology attractive and implementable.

1.1.1.5 Performance analysis of agile manufacturing along specified time horizons

Agile manufacturing requires complete integration of highly trained, motivated and empowered employees working in teams; the use of advanced design, manufacturing and administrative technologies; integration of operations with suppliers and customers; concurrent engineering; and knowledge management (Vazquez-Bustelo *et al.,* 2007). Hence it is obvious that AM requires huge investments in different areas in order to enhance the agility and therefore, its impact on business performance needs to be studied, monitored and evaluated to justify such investments. A methodology is proposed by combining Fuzzy Analytic Hierarchy Process and Performance Value Analysis to analyze agile manufacturing performance along specified time horizons. It is also to quantify, evaluate and compare the implementation performance of Agile Manufacturing (AM) program along Agile Manufacturing Enablers (AMEs) at different timeline. Broadly eleven Agile Manufacturing Enablers (AMEs) were identified and classified into three Significant Categories (SCs). Featuring these SCs and AMEs, Graph Theoretic Approach (GTA) was proposed for evaluating the implementation performance of AM programs. The analysis was further extended to evaluate the performance along the timeline and eventually compare the results with different performance scenarios to set the future targets.

1.1.1.6 A benchmarking approach for enhancing agility in manufacturing environment

All organizations focusing on agility should strive for enhancing the agility level to be sustainable in the long run. AM implementation is a prerequisite for an organization to be agile. In order to consistently operate AM Systems under ever changing operating environments, it is important to measure and improve the agility of the manufacturing systems (Routroy *et al.,* 2015a). Although benchmarking approach has been applied successfully in many areas and many research papers have been reported for improving the performance of the system, not much literature is available on the application of benchmarking approach for AM. Hence, a complete and structured conceptual AM framework is developed based on benchmarking approach. The step by step implementation process of the proposed generic benchmarking framework is also presented. It consists of nine phases (cross functional team formation; identification of the enablers, barriers and outcomes; analysis of enablers and barriers for selection; identification of benchmarking partners for selected barriers and enablers; gap analysis;

development of strategies on the basis of gap analysis; implementation of proposed strategies; monitoring the performance through the selected outcomes; and continuous improvement) and each phase has number of steps. The total number of steps for all the phases is 38. Each step is developed and discussed. The proposed framework provides a systematic direction for measuring and enhancing agility on a continuous basis. The proposed framework is conceptually developed and not empirically validated.

1.1.2 Thesis Outline

In the first chapter of the thesis, the backdrop of Agile Manufacturing along with the significance of current research focus is introduced.

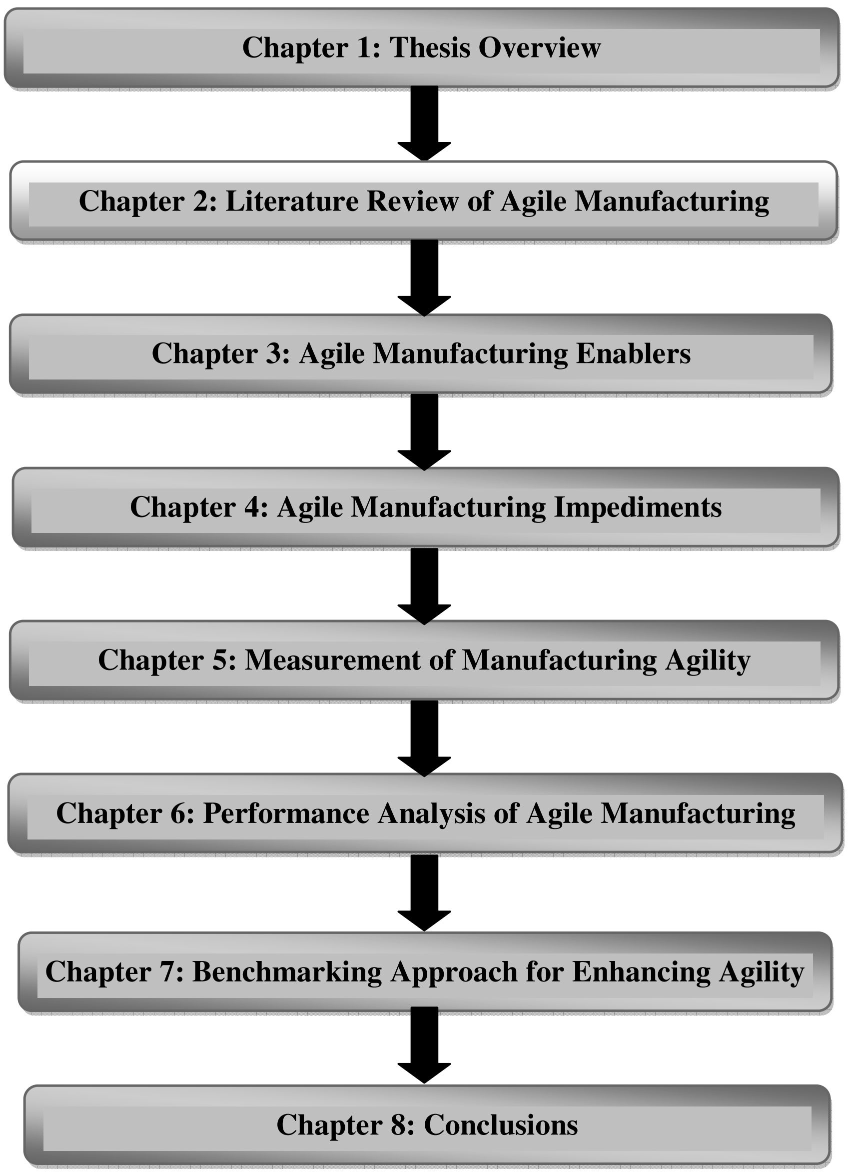

Figure 1.1: Thesis outline showing the flow of research work

As shown in the Figure 1.1, the literature review of agile manufacturing has been provided in the second chapter of the thesis. The analysis of various dimensions of AM was carried out critically and research gaps were identified. In Chapter 3, a generic model using ISM - FMICMAC was developed to strategically select and focus the right Agile Manufacturing Enablers on the basis of their interactions for successful implementation of AM in a specific manufacturing environment. Further in the Chapter 4, the focus is on managing and mitigating agile manufacturing impediments. Generic methodologies were proposed and developed using Fuzzy DEMATEL and ISM – FMICMAC method for allocating efforts and resources in a specific manufacturing environment to mitigate their impact on AM performance.

Further in the Chapter 5, the focus is on measuring agility by capturing multiple experts' judgment. A generic methodology was proposed using fuzzy Analytic Hierarchy Process (AHP) and the triangular fuzzy numbers (TFNs) to determine Fuzzy Agile Manufacturing Index (FAMI) for the different time periods. The performance analysis of AM and AMEs was carried out in Chapter 6. For the performance analysis of AM, the outcomes and their corresponding key performance indicators were identified and a generic methodology using PVA was developed. For the performance analysis of AMEs, a generic methodology using graph theoretic approach was developed. The Chapter 7 deals with development of conceptual benchmarking framework for agility enhancement of AM. The step by step implementation process of it was discussed in this Chapter. Finally, the results obtained from the studies are concluded along with the possible future research directions in Chapter 8.

CHAPTER 2

Literature Review of Agile Manufacturing

2.1 Introduction

Towards the end of the 20th century, manufacturing and distribution environments were being exposed to ever increasing levels of uncertainty, management of which was an enigma for any organization attempting to compete in challenging markets (Thompson, 1967). Also, Modern manufacturing system has come a long way from the brute Mass Production System (MPS) to that of highly flexible and customized production based on customers' preferences. Many industries, especially those in FMCG, automotive, fashion and food industries had a tough time to economically sustain in rapidly changing competitive scenario. Globalization of operations put forth numerous possibilities and challenges. This necessitated a revamp of traditional style of product design, process planning, manufacturing planning, logistics (i.e. both inbound and outbound), inventory management techniques etc. (Cheng *et al.*, 1998). Vokurka and Fliedner (1998) reviewed the historical competitive environment and changes in strategic responses and reviewed relevant research on competitive capabilities. They suggested that the trade-offs exist in these capabilities and offered a model which suggests how firms may build a cumulative and lasting improvements in strategic competitive capabilities including agility. Lee and Lau (1999) discussed the concept of a new manufacturing paradigm which is moving away from mass production to one based on fast-responsiveness and flexibility, capitalizing on the rapid advancement in internet technologies and factory-on-demand mode of production. The new manufacturing paradigm has been called as AM. AM has evolved as an alternative manufacturing paradigm owing to new challenges faced by the industries due to anticipated and unanticipated changes in manufacturing scenario. Newer technologies, materials, manufacturing strategies, and sporadic economic conditions have introduced an element of "uncertainty" and challenged the organization's sustainability (Vázquez-Bustelo *et al.*, 2007). These factors in addition to increased customers' desire for customized quality products in the shortest possible time and at the most affordable cost have led to the search of a better manufacturing philosophy. AM provides the flexibility and responsiveness to address the various issues raised above. Flexibility is defined as the ability to quickly adapt the resources to produce the product desired by the customer, while the term responsiveness defines the ability to heed the customers' requirements and align its processes to facilitate the production in shortest possible time. AM is defined as the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services (Gunasekaran, 2001). Duguay *et al.* (1997) compared mass production and flexible/agile production through a historical perspective and outlined the major differences between them. Jackson and Johanssson (2002) presented an investigation into the concept of agility and how it can be applied within industry. Agility enables the industry to deliver customized, equitably priced and superior quality product in an efficient and time bound manner. It streamlines the internal and external disturbances of the industry arising due to the uncertain market condition. The main objective of agility is to offer the speed needed to change in response to the volatile and unanticipated market. Agility comes from the amalgamation of factors like operating decisions, information integration, management practices, effective integration of subsystems, development of appropriate controls and performance measures, and compatibility between production system design and organization structure.

2.1.1 Evolution of Agile Manufacturing

The manufacturing paradigm has shifted from that of Craft Manufacturing to Mass Production and then to Lean Manufacturing (LM). The present era is of AM. The progression has been due to the changing focus of manufacturing objectives and influence of manufacturing management techniques. New management techniques have come in a way to better understand the different aspects of manufacturing from the perspective of human resource, suppliers/vendors, impact of inventory management, marketing, sales etc. The aim of any business is to maximize its profits. Mass Production tried to manufacture a single product in huge numbers to reduce the per-unit cost of production and used the volume to drive the profits. This method could not sustain for long as customers' preferences were changing and manufacturing with reduced number of units was not economically viable (Iacocca Institute, 1991). The next shift in paradigm was LM that focused on reducing the wastes to improve the processes and reduce the production time and deliver the quantity demanded by the customer. The objective is to provide the customer a quality product in the right quantity at the most competitive price. LM relies more on optimization of process and inventory to reduce manufacturing time and associated costs. This leads to better utilization of resources and time and ultimately leading to quality production at lowest costs to customer. The emphasis is more on cost and process optimization. Flexibility to produce different varieties of products is possible to some extent only if it is predetermined. Any abrupt changes in product varieties cannot be implemented and supported by LM.

AM is alleged to be the next progression of LM and flexible manufacturing, but it is a new system of manufacturing which borrows concepts from LM and flexible manufacturing with those of supply chain management to form a new manufacturing strategy. LM is most suited when the demand is well known in advance and a steady production is anticipated. The inventory management and resource allocation is streamlined based on just in time fundamentals. Abrupt changes in products cannot be accommodated dynamically. Flexible Manufacturing System (FMS) which uses computer numeric control/direct numeric control technology and Group Technology, facilitates scope for dynamic product changes during manufacturing (Wang *et al.* 1996). AM strives to be dynamically flexible and responsive to customer preferences and aims to provide the product within the time frame expected by customer. Hence, the emphasis on cost savings is not of primary importance (James-Moore, 1997). By being able to respond quickly to dynamic situations, it is able to overcome the barrier in LM. Harrison (1997) presented that comparison of LM to the emerging AM system. Narasimhan *et al.* (2006) presented a review of leanness and agility with respect to manufacturing paradigms and performance capabilities. Also an empirical study to determine if lean and agile forms occur regularly in manufacturing plants was presented. Yusuf and Adeleye (2002) presented a comparative study of lean and agile manufacturing with a related survey of current practices in UK. AM has been proposed and conceptualized in early 1990s. Goldman and Nagel (1993) explored the impact of technological innovation and organizational innovations on the competitiveness of manufacturing enterprises in US industries. Richards (1996) explained the history and concept of agility as applied to manufacturing. O'Connor (1994) provided an overview of implementing AM in welding and milling operations. Ross (1994) presented AM as the natural evolutionary confluence of three key business concepts - flexible manufacturing, integrated product development (i.e. concurrent engineering) and Strategic Partnering. The AM paradigm had been the focus of many researchers and various theories have been put forth considering different factors. Forsythe (1995) presented a brief overview of AM paradigm and emphasised the human factors contributing to it. Maskell (1996) discussed difference between AM and world class manufacturing and evolution of AM from other manufacturing strategies. The focus of AM is not only on quality of product but predominantly on ensuring that the customer gets the product as customer desires in the shortest possible time. Cost reduction is not the primary objective in AM, rather degree of quickness is. AM promotes flexibility and responsiveness by organizing the processes and resources in tune with the customer expectations.

2.1.2 Various Reported Definitions of AM

AM is defined by researchers in many ways depending upon the nature of manufacturing. It can be rapid changeover from assembly of one product to the assembly of different product (Quinn *et al*, 1997), new production model to resolve the limitations of lean manufacturing (Adeleye and Yusuf, 2006 and Yusuf and Adeleye, 2002) and combine the efficiency of lean manufacturing with operational flexibility of flexible model (Adeleye and Yusuf 2006).Many authors have laid emphasis on customization, reduction in manufacturing lead time, optimal designs, reduction in manufacturing costs, increased product varieties, predicting and responding to the market trends, satisfaction of customer requirements and experience etc (Quinn *et al.*, 1997; Gaafar and Masoud, 2005; Ramesh and Devadasan, 2007, Vinodh *et al.*, 2008; and Mengoni *et al.*, 2009) as indicators of good manufacturing performance which in turn will make the manufacturing system economically sustainable, stable and capable of generating profits.

The ability to be flexible and responsive is called agility. AM is defined less as standalone and more with respect to agility. Literature is abundant with definitions of what constitutes agility. Agility has been defined as change proficiency which includes cost, time, scope and robustness of change (Dove *et al.*, 1997). Sarkis (2001) defined agility as the ability to thrive in an environment of continuous and often unanticipated change. Kidd (1995) defined agility concept to comprise two factors – responding to changes and exploiting changes, and taking advantage of changes as opportunities. AM has been widely accepted as a new way of manufacturing and is been implemented in various types of industries. Many of the definitions are extensions of LM and FMS with addition of flexibility and responsiveness. Few have defined it as a revolutionary type of manufacturing with emphasis on customer and human workforce which was neglected in the earlier manufacturing systems. AM is also defined as a synergy of technology, management and workforce (Goldman and Nagel, 1993, Gunasekaran, 1999). Most researchers have stressed on the ability to be responsive as one of the key identifying feature of AM. Flexibility and responsiveness is attributed to creation of virtual enterprises, development of key suppliers, relying on the core-competency of the organization and importance given to workforce development (Kidd, 1995; Dove *et al.*, 1997; Yusuf *et al.*, 1999; Gunasekaran, 1999; Yusuf and Adeleye, 2002).AM is also known for "mass customization" as it has the capability to produce and delivery product according to the dynamic specification and requirements of customers efficiently in customer specified time while maintaining superior quality. The main points in the definition of various authors may be summarized as follow: high quality and highly customised products (Goldman and Nagel, 1993; and Kidd, 1995), products and services with high information and value-adding content (Goldman and Nagel, 1993; and Goldman *et al.*, 1995), mobilisation of core competencies (Goldman and Nagel, 1993; and Kidd, 1995), responsiveness to social and environmental issues (Goldman and Nagel, 1993; and Kidd, 1995), synthesis of diverse technologies (Burgess, 1994; and Kidd, 1995), response to change and uncertainty (Goldman and Nagel, 1993; and Goldman *et al.*, 1995), and intra-enterprise and inter-enterprise integration (Kidd, 1995; and Youssef, 1994). AM is a powerful manufacturing paradigm enabling the production of customized products coupled with time compression in a cost effective manner (Vinodh *et al.*, 2015).

Table 2.1: Definitions of agile manufacturing

S.No.	References	AM Definitions
1	Iacocca Institute (1991)	AM is a 21^{st} century manufacturing strategy which is capable of responding to the fast-changing market needs and manufacturing demands of a global economy.
2	Goldman and Nagel (1993)	AM is a new generation manufacturing strategy, which can be achieved by integrating three resources – technology, management and workforce into a coordinated, interdependent system.

S.No.	References	AM Definitions
3	Goldman and Nagel (1993)	AM is a new production model that has resulted from changes in the environment
4	Kidd (1995)	AM is a manufacturing concept, which is capable of responding rapidly to changes in customer demand and will be able to take advantage of windows of opportunity that, from time to time, appear in the market place.
5	Kidd (1995)	AM is built around the synthesis of a number of enterprises that each have some core skills or competencies which they bring to a joint venturing operation, which is based on using each partner's facilities and resources.
6	O'Connor (1994)	AM is a set of advanced manufacturing concepts characterized by their ability to allow a rapid response to continuously changing customer requirements.
7	Youssef (1994)	AM is a manufacturing system with extraordinary capability to meet the rapidly changing needs of the marketplace. A system that can shift rapidly amongst product models or between product lines, ideally in real-time response to customer demands
8	Goldman *et al.* (1995)	AM is the agility of operating profitably in a competitive environment of continually and unpredictably, changing customer opportunities.
9	Goldman *et al.* (1995)	AM is an essential condition to survive in such an environment designated as turbulent.
10	Iyer and Nagi (1995)	AM unit is a customer-centred organization geared for rapid delivery of new, high quality and easily customized products.
11	Quinn *et al.* (1996)	AM is the ability to accomplish rapid changeover between the manufacture of different assemblies utilizing essentially the same work-cell.
12	Devor *et al.* (1997)	AM is evolved as a response to the drastic changes in the manufacturing processes by discarding the traditional processes that are no longer valid to thrive in this competitive age, making an organization flexible and responsive to market changes.
13	Kusiak and He (1997)	AM is driven by the need to respond quickly to the changing customer requirements.
14	Quinn *et al.* (1997)	AM is the ability to accomplish rapid changeover between the manufacture of different assemblies.

S.No.	References	AM Definitions
15	Cheng *et al.* (1998)	AM is an emerging technology for a firm to achieve flexibility and rapid responsiveness to the changing market and customer's needs.
16	Gunasekaran (1998)	AM is linking innovations in manufacturing, information and communication technologies with radical organisational redesign and new marketing strategies
17	Quintana (1998)	AM is a manufacturing system which is able to produce a large variety of products efficiently and be reconfigurable to accommodate changes in the product mix and product designs.
18	Gunasekaran (1999)	AM is achieved by integrating organisations, people and technology into a meaningful unit by deploying advanced information technologies and flexible organisational structures to support highly-skilled, knowledgeable and motivated people
19	Yusuf *et al.* (1999)	AM is a manufacturing system with flexible technology, qualified and trained human resources, and shared information that responds quickly to continuous and unpredictable changes in customer needs and desires and in market demand.
20	Zhang and Sharifi (2000)	AM understands and responds to changes, and taking advantage of changes through strategic utilization of managerial and manufacturing methods and tools.
21	Gunasekaran (2001)	AM is defined as the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services
22	Hormozi (2001)	AM is a new and revolutionary way of manufacturing and assembling products.
23	Hormozi (2001)	AM is a top-down enterprise-wide effort that supports the time-to-market attribute of competitiveness.
24	Hooper *et al.* (2001)	AM is a manufacturing system with extraordinary capability to meet the rapidly changing needs of the market place.
25	Hooper *et al.* (2001)	AM is a system that can shift quickly amongst product models or between product lines, ideally in real-time response to customer demand.
26	Sarkis (2001)	AM is a strategy that contains LM and flexible manufacturing and addresses the business enterprise world.

S.No.	References	AM Definitions
27	Yusuf and Adeleye (2002)	AM is encompassed with reprogrammable utilities which are programmed at any time by the knowledge workers.
28	Yusuf and Adeleye (2002)	AM has arisen as a new production model to resolve the limitations of LM
29	Brown and Bessant (2003)	AM is defined as the capability of an organization to survive in the competitive environment of continuous and unanticipated changes to respond quickly to dynamic market conditions.
30	Stratton and Warburton (2003)	AM is an approach to manufacturing which is focused on meeting the needs of customers while maintaining high standards of quality and controlling the overall costs involved in the production of a particular product
31	Vázquez-Bustelo *et al.* (2007)	AM is a production model that responds to changes of the environment to provide flexibility, speed, quality, service and efficiency through the integration of high-tech, highly qualified human resources and organization.
32	Bottani (2010)	AM is considered a very important and appropriate course of undertakings in a market that demands quick answers to their rapid changes
33	Vinodh and Kuttalingam (2011)	AM is a manufacturing paradigm that enables the industries to respond to the dynamic demands of the customers quickly.
34	Elmoselhy (2013)	AM is a manufacturing strategy, which can enable a company to be flexible enough to quickly respond to the dynamic demands of the customers and manufacture products with many varieties and innovative features

2.2 Agile Manufacturing Literature Review

AM was the philosophy postulated by Iacocca Institute to overcome some of the short comings of lean philosophy (Iacocca Institute, 1991). Many practitioners, who were advocating the lean concept, had to face newer challenges from the uncertain and ever-changing customer demand. When the lean philosophy failed to address these issues, the AM was conceptualized. The objective was to thrive in an unpredictable and uncertain business environment and leverage it for business opportunities. This required the AM to be “flexible” and “responsive” to the market (O’Connor, 1994; and Kidd, 1995). AM moved away from the traditional mass production and LM philosophy to bring in a manufacturing paradigm that is equally proficient at handling a variety of products, large variation in volume of production, and yet be profitable business venture. The focus of AM was not to "reduce costs" but to be "most responsive". The emphasis to cost is given a secondary consideration. This does not mean that lean concepts of reducing wastes is not adhered to, rather AM strives to make the processes as optimized as possible. It breaks the shackles of predetermined, demand-based manufacturing which made it inflexible and apathetic. Since the emphasis has always been on the ability to respond and quickly meet the customer's demands, the processes have been made to be as flexible as possible. AM strongly advocates virtual enterprises concept as it helps to leverage the competencies of partners, based on the demand, and thus reduce the response time. The design and manufacturing processes too have to be made flexible and responsive to reduce the design and manufacturing planning time.

AM is being well researched manufacturing strategy by many industries wishing to leverage the advantages that accrue. Industries irrespective of their line of business are seeking AM. Industries that are sensitive to customer preferences like FMCG, food and beverages, fashion, footwear, automotive, electrical - electronic goods manufacturers, projects based industries etc. are shifting their focus towards AM. Various authors have presented articles regarding the need for implementation of AM in the above type of industries. Phillips (1999) provided a comparison study of lean and AM being applied in automotive industry and postulated how AM can be implemented in aerospace industry. Lee and Lau (1999) discussed application of AM in an Electronics and Electrical appliances industry. Sohal (1999) traced the development of AM in Australia and the studies undertaken by Australian Manufacturing Council in 1990s in the Textile/Clothing/Footwear industry. Prince and Kay (2003) presented Virtual Group concept in AM for Cables industry. Implementations in Car and Computer industry have been shown by Brown and Bessant (2003).

Many researchers have studied the existing scenario of AM implementation process in various industries i.e. textile and clothing industry (Bruce *et al.*, 2004; Zerenler, 2007; and Su *et al.*, 2008), motor coach industry (Frayret *et al.*, 2001), cables industry (Prince and Kay, 2003), automotive industry (Elkins *et al.*, 2004), electronic industry (Deif and ElMaraghy, 2007), construction industry (Chen *et al.*, 2007; and

Gosling *et al.*, 2007), manufacturing industries (Anuziene and Bargelis, 2007; Krishnamurthy and Yauch, 2007; Vázquez-Bustelo *et al.*, 2007; Zhang and Sharifi, 2007; Almahamid *et al.*, 2010; Lotfi *et al.*, 2013; and Goriwondo *et al.*, 2013), FMCG industries (Agarwal *et al.*, 2006), Indian manufacturing industries (Vinodh *et al.*, 2010a; Vinodh and Devadasan, 2011; Vinodh *et al.*, 2012c; and Aravind *et al.*, 2013), welded construction and metal structures sector (Bottani, 2009), car manufacturing industry (Gharakhani *et al.*, 2013), Indian electronic/rotary switches manufacturing industry (Bottani, 2010; Ismail *et al.*, 2011; and Loforte and Timóteo, 2010), SMEs (Vinodh, 2011; Vinodh and Chintha, 2011; Vinodh and Aravindraj, 2012; and Vinodh *et al.*, 2013) and transformer industry (Vinodh and Aravindraj, 2013). Hallgren and Olhager (2009) studied the AM implementations in manufacturing firms in Europe, Asia, and North America. Jassbi *et al.* (2010), developed models to implement AM in Iran.

Table 2.2: Agile manufacturing literature review

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
1	Goldman and Nagel (1993)	A	USA	Explored the impacts of technological and organizational innovations on the emergence of the highly responsive AM enterprise.	Comparative	International Journal of Technology Management	-
2	Fung and Ren (1994)	A	Hong Kong	Explained the design and modelling of a decision support framework for agile enterprises.	Descriptive	Industrial Technology	-
3	Graham and Ragade (1994)	A	USA	Discussed the requirements for an intelligent concurrent engineering design support station for AM that will allow the design engineer to evaluate design modifications.	Descriptive	IEEE International Conference	-
4	O'Connor (1994)	A	USA	Presented an overview of AM and discussed it's applications in Milling and Welding operations.	Conceptual	Mechanical Engineering	-
5	Rocha and Ramos (1994)	A	Portugal	Presented task and execution planning for flexible and AM systems, which will automatically generate programs for Robots, AGVs, and NC machines.	Descriptive	IEEE International Conference	-
6	Ross (1994)	P	USA	Presented AM as the natural evolutionary confluence of three key business concepts - Flexible Manufacturing, Concurrent Engineering, and Strategic Partnering.	Conceptual	World Class Design to Manufacture	-
7	Sanderson *et al.* (1994)	A	USA	Presented how to achieve multi-path agility and improvements in productivity and quality.	Descriptive	IEEE International Conference	Electronics Manufacturing
8	Walker *et al.* (1994)	A	USA	Discussed the design of knowledge based systems and the role of artificial intelligence in AM.	Descriptive	Unpublished Report	-
9	Barbuceanu and Fox (1995)	A	Canada	Addressed the coordination issues at the tactical and operational levels during the construction of an agent based infrastructure for AM.	Descriptive	International Joint Conference on Artificial Intelligence	-
10	Forsythe (1995)	P	USA	Presented an overview of AM paradigm and emphasized the human factors contributing to AM.	Conceptual	Sandia National Labs.	-
11	Gmytrasiewicz *et al.* (1995)	A	USA	Presented an approach by combining agent oriented paradigm with operations research techniques for AM system design.	Descriptive	International Conference on Robotics and Manufacturing.	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
12	Iyer and Nagi (1995)	A	USA	Proposed a systematic procedure to combine independent similarity indexes to create a unique measure for searching and sorting parts in AM.	Descriptive	Master's thesis, State University of New York at Buffalo	-
13	Jain (1995)	A	Singapore	Described the role of modelling and analysis during the AM system development cycle and proposed a Virtual Factory Framework for their systematic and efficient use.	Descriptive	IEEE International Conference	-
14	Kidd (1995)	P	UK	Presented a literature review and features of AM.	Review	AM Colloquium	-
15	Parunak (1995)	A	Netherland	Described the problem of AM enterprises in detail and the need to dynamically analyze them.	Descriptive	Industrial Technology Institute	Automotive
16	Sadeh *et al.* (1995)	A	USA	Summarized initial work towards the development of an Integrated Process Planning/Production Scheduling (IP3S) Shell for AM.	Descriptive	Carnegie-Mellon University Pittsburgh Robotics Inst.	-
17	Cho *et al.* (1996)	A	South Korea	Presented various AM activities in South Korea.	Descriptive	Computers and Industrial Engineering	Consumer Electronics Industry
18	Graves *et al.* (1996)	A	USA	Discussed the conceptual methodologies to address the issues of cost and cycle time estimation in an AM environment.	Conceptual	IEEE International Conference	Electronics Manufacturing
19	Hong *et al.* (1996)	A	Canada	Developed a mathematical model of flexible fixturing systems and described the process of locating and clamping by fixturing systems for AM.	Descriptive	IEEE International Conference	-
20	Jung *et al.* (1996)	A	South Korea	Provided a primary sketch of architectural requirements for rapid development of AM systems.	Descriptive	Computers and industrial engineering	-
21	Maskell (1996)	P	USA	Discussed the differences between AM and WCM, and evolution of AM from other manufacturing strategies.	Comparative	International Advances in Engineering and Technology	-
22	Minis *et al.* (1996)	A	USA	Presented a generative approach to obtain feedback about a new product embodiment based on high-level process plans for AM.	Descriptive	Maryland University College For Systems Research	Mechanical and Electronic products

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
23	Quinn *et al.* (1996)	A	USA	Presented a design for AM work cells for light mechanical assembly of products made from similar components (i.e. Parts families).	Descriptive	IEEE International Conference on Robotics and Automation	Mechanical assembly
24	Rajan (1996)	A	USA	Presented an agent based fractal model of AM enterprises.	Descriptive	AI and Manufacturing Research Planning Workshop	-
25	Richards (1996)	P	USA	Explained the history and concept of agility as applied to manufacturing.	Conceptual and Review	Production and Inventory Management Journal	Aerospace Industry
26	Shen (1996)	P	USA	Discussed the global movement towards an agile and green manufacturing environment and its impact on metal cutting in the automotive industry.	Descriptive	Surface and Coatings Technology	Automotive industry
27	Wang *et al.* (1996)	A	USA	Presented concepts of an Internet assisted manufacturing system for AM practice.	Conceptual and Descriptive	Journal of Materials Processing Technology	Manufacturing
28	DeVor *et al.* (1997)	A	USA	Discussed the genesis of several of the AM Research Institutes (AMRIs) and their on-going activities and results.	Descriptive	IIE Transactions	-
29	Duguay *et al.* (1997)	A	Canada	Compared mass production and Flexible/Agile Production through a historical perspective and outlined the major differences between them.	Comparative	International Journal of Operations and Production Management	-
30	Gould (1997)	P	UK	Identified the elements of agility, and how they relate to the other buzzwords of our time.	Conceptual	Manufacturing Engineer	-
31	Harrison (1997)	A	UK	Presented comparison of LM to the emerging AM system.	Comparative	IEEE Colloquium	-
32	Iyer and Nagi (1997)	A	USA	Addressed the problem of identifying existing parts that are similar, in one or many characteristics, to a new part at the design stage in an agile enterprise environment.	Descriptive	IIE Transactions	Manufacturing
33	James-Moore (1997)	A	UK	Addressed the concept of "agility" from literature and stated that cost is given lesser precedence than the ability to meet the customers' requirement.	Conceptual and Empirical	The Institution of Electrical Engineers.	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
34	Jo *et al.* (1997)	A	USA	Presented the architecture of the graphical simulator and presented a framework for virtual testing of AM software using 3D graphic simulation.	Descriptive	IEEE International Conference on Robotics and Automation	-
35	Kim *et al.* (1997)	A	USA	Developed software architecture for control of an AM work cell, and demonstrated its flexibility with rapid changeover and introduction of new products.	Descriptive	IEEE International Conference on Robotics and Automation	-
36	Kusiak and He (1997)	A	USA	Proposed three rules applicable to the design of products for agile assembly from an operational perspective.	Descriptive	International Journal of Production Research	-
37	Lee *et al.* (1997)	A	USA	Described AM database system designed for capturing and manipulating the operational data of a manufacturing cell.	Descriptive	IEEE International Conference on Robotics and Automation	-
38	Litsikas (1997)	A	USA	Discussed the role of Quality to enhance Agility of a company.	Conceptual	Quality	-
39	Meade and Rogers (1997)	A	USA	Discussed the system of business processes, agility theory and the Analytic Network Process (ANP) methodology.	Descriptive	International Conference on Management and Technology	Conduct manufacturing Industry
40	Merat *et al.* (1997)	A	USA	Developed agile software architecture for rapid introduction of new assemblies through code re-usability.	Descriptive	IEEE International Conference on Robotics and Automation	-
41	Plonka (1997)	A	USA	Addressed the demands that lean and AM initiatives will place on the current and emerging workforce to achieve increasing levels of quality and flexibility with lower costs and shorter product life cycles.	Comparative	Human Factors and Ergonomics in Manufacturing	-
42	Song and Nagi (1997)	A	USA	Addressed the design and implementation of an AM information system integrating manufacturing databases dispersed at various partner sites.	Descriptive	IIE Transactions	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
43	Cheng *et al.* (1998)	A	UK	Presented a new approach to implementing agile design and manufacturing concepts.	Descriptive and Empirical	Journal of Materials Processing Technology	Roller Bearing Industry
44	Gunasekaran (1998)	A	UK	Presented a conceptual framework for the development of an AM system and future research directions.	Conceptual	International Journal of Production Research	-
45	Kasarda and Rondinelli (1998)	A	USA	Identified the components of logistical support system that is needed to stimulate AM and examined the strategic integration of components into a unified business support system.	Descriptive	Sloan Management Review	-
46	Lee (1998)	A	South Korea	Presented a design for agility rule which reduces manufacturing lead times and costs associated with machine relocation problems.	Descriptive	International Journal of Production Research	-
47	Newman *et al.* (1998)	A	USA	Described advances in developing key software, sensing/control, and parts-handling technologies enabling robust operation of an AM work cells.	Descriptive	International Conference on Robotics and Manufacturing	-
48	Quintana (1998)	A	USA	Described the manufacturing industry on US border, and the need for agile and lean production to stay competitive.	Descriptive and Empirical	International Journal of Operations and Production Management	Manufacturing industry
49	Subbu *et al.* (1998)	A	USA	Presented a comparison of the performance of a fuzzy logic controlled genetic algorithm and a parameter tuned genetic algorithm for an AM application.	Descriptive	IEEE ISIC/CIRA/ISAS Joint Conference	-
50	Tan (1998)	A	Turkey	Discussed the relationship between AM and management of variability.	Exploratory	International Transactions in Operational Research	-
51	Vokurka and Fliedner (1998)	A	USA	Developed a model which suggested how firms can build cumulative and lasting improvements in strategic competitive capabilities including agility.	Descriptive	Industrial Management and Data Systems	-
52	Christian and Zimmers (1999)	P	USA	Reviewed manufacturing scenario to seek a better strategy to deal with unpredictable changes and presented in support of AM.	Empirical	Quality Progress	Food industry

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
53	Gunasekaran (1999)	A	USA	Reviewed literature with an objective to identify key strategies and techniques of AM.	Empirical	International Journal of production economics	-
54	Huang and Nof (1999)	A	USA	Proposed that error detection and recovery, and conflict resolution were two significant functions of operational and logistics agility.	Conceptual/Descriptive	International Journal of Agile Management Systems	-
55	Katayama and Bennett (1999)	A	Japan	Presented a comparison study of agility, adaptability and leanness in the context of modern competitive situation in Japan.	Comparative	International Journal of production economics	-
56	Lee and Lau (1999)	A	Hong Kong	Discussed the concept of new manufacturing paradigm that is based on fast responsiveness and flexibility called as AM.	Conceptual	International Journal of Agile Management Systems	Electronic and Electrical appliances
57	McGaughey (1999)	A	USA	Discussed the role of internet technology in enabling AM by enhancing the communication between various stakeholders.	Descriptive	International Journal of Agile Management Systems	-
58	Meade and Sarkis (1999)	A	USA	Introduced a decision methodology and structure for manufacturing agility improvement.	Descriptive	International Journal of Production Research	-
59	Monplaisir *et al.* (1999)	A	USA	Described the development and evaluation of computer supported collaborative work prototypes to aid the systematic evaluation of AM systems.	Empirical and Descriptive	Human Factors and Ergonomics in Manufacturing	-
60	Parkinson (1999)	P	UK	Described the principles underpinning AM.	Conceptual	Work Study	-
61	Phillips (1999)	P	UK	Provided a comparison study of lean and AM being applied in automotive industry and postulates how AM can be implemented in aerospace industry.	Comparative	International Journal of Agile Management Systems	Aerospace Industry
62	Sharifi and Zhang (1999)	A	UK	Discussed the concepts and the development of a methodology to achieve agility based on responding to changes.	Conceptual and Descriptive	International Journal of production economics	-
63	Sharp *et al.* (1999)	A	UK	Proposed a conceptual model to identify where UK's best practice industries in their quest to become AM organizations.	Descriptive	International Journal of production economics	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
64	Sohal (1999)	A	Australia	Traced the development of AM in Australia and the studies undertaken by Australian Manufacturing Council in 1990s.	Empirical	International Journal of Agile Management Systems	TCF (Textiles/Clothing/Footwear)
65	Tomita *et al.* (1999)	P	Japan	Proposed flow oriented approach for human-centered AM Systems information, to accelerate diversified autonomous improvement activities.	Descriptive and Empirical	Integration of Heterogeneous Systems Proceedings.	-
66	Towill and McCullen (1999)	A	UK	Presented problem areas associated with agile supply chain dynamics and listed a set of supply chain material flow principles.	Empirical	International Journal of Logistics Management	-
67	Vernadat (1999)	A	France	Discussed organizational, technological and human aspects of agility with respect to product design, manufacturing system design and innovation management.	Conceptual	International Journal of Agile Management Systems	-
68	Wong and Whitman (1999)	A	USA	Presented the comparison of agility, leanness and flexibility, and a methodology to attain agility.	Comparative	International Conference on Industrial Engineering Theory, Applications and Practice	-
69	Wu *et al.* (1999)	A	China	Presented a brief overview of task decomposition for manufacturing of a product in multisite environment and to select partner in AM environment.	Descriptive	Journal of Intelligent Manufacturing	-
70	Yusuf *et al.* (1999)	A	UK	Identified the drivers of agility and discussed the portfolio of competitive advantages that have emerged over time as a result of the changing requirements of manufacturing.	Descriptive	International Journal of production economics	-
71	Zhang *et al.* (1999)	A	China	Identified the various factors that are critical to the success of an AM system.	Descriptive	International Journal of production economics	-
72	Abdel-Malek *et al.* (2000)	A	USA	Presented a method to design, build and implement a flexible manufacturing solution in agile enterprises.	Descriptive and Empirical	International Journal of Agile Management Systems	-
73	Bamber *et al.* (2000)	A	UK	Examined systems thinking and proposed a holistic approach to develop an integrated management system that supports the concepts of AM.	Empirical	International Conference on Systems Thinking in Management	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
74	Bhandarkar and Nagi (2000)	A	USA	Proposed a feature extraction system taking as input a STEP file and generating as output a STEP file with form-feature information for AM.	Descriptive	Computers in Industry	-
75	Chan *et al.* (2000)	A	Hong Kong	Proposed an object-oriented architecture that supports design and implementation of highly reconfigurable control systems for AM cells.	Descriptive	IEEE International Conference	-
76	Fujii *et al.* (2000a)	A	Japan	Proposed a Distributed Virtual Factory (DVF) concept in AM environment that consists of distributed precise simulation models connected by several synchronization mechanisms.	Descriptive	International Journal of Production Research	-
77	Fujii *et al.* (2000b)	A	Japan	Proposed a manufacturing system locating machining cells in a square array which is considered as an AM system.	Descriptive	Winter Simulation Conference	-
78	Kollura *et al.* (2000)	A	USA	Presented the outline of a conceptual control and communications architectural framework enabling AM enterprises.	Descriptive	IEEE International Conference on Robotics and Automation	-
79	Meredith and Francis (2000)	A	UK	Discussed competitive advantage, order winning criteria and increasing global and local competition in the context of AM.	Descriptive	The TQM Magazine	-
80	Newman *et al.* (2000)	A	USA	Presented recommendations for design of AM systems based on review of both physical and software design choices.	Descriptive	IEEE Transactions on Robotics and Automation	-
81	Van (2000)	A	Netherland	Explored the relation between agile management and time-based competence management, and studied its adoption in small batch discrete parts manufacturing environments.	Exploratory	International Journal of Agile Management Systems	-
82	Van *et al.* (2000)	P	Netherland	Presented a framework for manufacture-to-order environments that enables and supports agile-based discrete parts manufacturing.	Descriptive	International Journal of Agile Management Systems	-
83	Xu *et al.* (2000)	A	China	Proposed a methodology for Agile Virtual Enterprises including enterprise architecture, reference model, and enterprise modelling methods.	Descriptive	Journal of Computer Science and Technology	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
84	Zhang and Sharifi (2000)	A	UK	Presented a methodology to assist manufacturing industries to achieve agility.	Empirical and Exploratory	International Journal of Operations and Production Management	-
85	Chan and Zhang (2001)	A	China	Proposed an Object and Knowledge-based Interval Timed Petri-Net (OKITPN) approach which provides an object-oriented and modular method of modelling manufacturing activities.	Descriptive	International Journal of Production Research	-
86	Christian *et al.* (2001)	A	UK	Provided an overview of the framework and tools developed for AM and Enterprise Centre to assist SME's in embracing agility concepts.	Descriptive	Manufacturing Information Systems Proceedings	-
87	Christopher and Towill (2001)	A	UK	Explored ways in which hybrid strategies (Lean and Agile) can be developed to create cost-effective supply chains.	Comparative	International Journal of Physical Distribution and Logistics Management	-
88	Frayret *et al.* (2001)	P	Canada	Presented a strategic framework for designing and operating agile networked manufacturing systems.	Descriptive	International Journal of production economics	Motor coach industry
89	He *et al.* (2001)	A	USA	Presented few scheduling problems associated with the assembly-driven product differentiation strategy in a general agile environment.	Descriptive	Robotics and Computer Integrated Manufacturing	-
90	Hooper *et al.* (2001)	A	UK	Proposed an operational cost environment for industries seeking to attain agility.	Descriptive	International Journal of Operations and Production Management	-
91	Hormozi (2001)	P	USA	Explained the potential benefits of successfully implementing AM compared to potential consequences of failing to implement it.	Conceptual	Benchmarking: An International Journal	-
92	Maskell (2001)	P	USA	Presented the key success factors for AM, which the industries must focus on.	Conceptual	Supply Chain Management: An International Journal	-
93	McCullen and Towill (2001)	A	UK	Presented the effect of an AM strategy on company's global supply chain.	Descriptive	Integrated Manufacturing Systems	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
94	Onuh and Hon (2001)	A	UK	Presented a comparative study of the effects of hatch patterns on stereo-lithography models using epoxy based resin in an AM environment.	Descriptive	Integrated Manufacturing Systems	-
95	Power *et al.* (2001)	A	Australia	Analyzed few Australian manufacturing companies to identify the factors critical for successful agile industries in managing their supply chains.	Exploratory	International Journal of Physical Distribution and Logistics Management	Manufacturing industry
96	Ramasesh *et al.* (2001)	A	USA	Proposed a quantitative analysis framework and a simulation methodology to explore the value of agility in financial terms.	Descriptive	Integrated Manufacturing Systems	-
97	Sanchez and Nagi (2001)	A	USA	Reviewed a wide range of literature on AM and proposed a classification scheme to organize them.	Empirical	International Journal of Production Research	-
98	Young *et al.* (2001)	A	UK	Proposed an Object Oriented model to an AM control system using UML which decomposes complex machine into small elements.	Descriptive and Empirical	International Journal of Advanced Manufacturing Technology	-
99	Chan and Zhang (2002)	A	Hong Kong	Presented a new architecture for an agile shop floor control system.	Descriptive and Empirical	International Journal of Advanced Manufacturing Technology	-
100	Gunasekaran and Yusuf (2002)	A	USA	Attempted to re-examine the scope, definitions and strategies of AM, and presented a framework based on major strategies and technologies of AM.	Conceptual and Descriptive	International Journal of Production Research	-
101	He and Babayan (2002)	A	USA	Developed optimal and heuristic methods for solving scheduling problems in AM.	Descriptive	International journal of Production Research	-
102	He and Grigoryan (2002)	A	USA	Proposed a double sampling s-chart to overcome the deficiencies inherent in the double sampling x-bar charts to evaluate AM.	Descriptive and Empirical	Quality and Reliability Engineering International	-
103	Huang (2002)	A	Taiwan	Presented a production model for manufacturers to apply in continuous and unanticipated changing competitive environment.	Descriptive	International Journal of Advanced Manufacturing Technology	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
104	Khoo and Loi (2002)	A	Singapore	Proposed to solve an assembly line balancing problem using a novel enhanced genetic algorithm approach.	Descriptive	International Journal of Advanced Manufacturing Technology	-
105	McCurry and McIvor (2002)	A	UK	Reviewed definitions of AM from literature.	Empirical	Irish Journal of Management	-
106	Monplaisir (2002)	A	USA	Presented the development and evaluation of CSCW prototypes to aid the systematic evaluation of AM systems.	Descriptive and Empirical	Group Decision and Negotiation	-
107	Poesche (2002)	P	Canada	Explored the business ethical implications of the evolution of manufacturing management starting at the pre-industrial workshops until the introduction of AM.	Comparative and Empirical	Journal of Business Ethics	-
108	Shih and Lin (2002)	A	China	Proposed development of an absolute agility index, a unique and unprecedented attempt in agility measurement using fuzzy-logic.	Descriptive	IEEE International Conference	-
109	Tang *et al.* (2002)	A	China	Proposed a pragmatic web-based platform based on CORBA to support virtual enterprising.	Descriptive	Concurrent Engineering	-
110	Tsourveloudis and Valavanis (2002)	A	Greece	Proposed a knowledge-based framework and presented as a candidate solution for the measurement and assessment of manufacturing agility.	Descriptive	Journal of Intelligent and Robotic Systems	-
111	Yang an Li (2002)	A	China	Proposed a multi-grade fuzzy assessment method to evaluate agility.	Empirical	Journal of Materials Processing Technology	Casting industry
112	Yusuf and Adeleye (2002)	A	UK	Presented a comparative study of lean and AM with a survey of current practices in UK.	Comparative	International Journal of Production Research	-
113	Zhou and Negi (2002)	A	USA	Presented distributed information system architecture for AM enterprises for heterogeneous partners to seamlessly integrate.	Descriptive	Journal of Manufacturing Systems	-
114	Brown and Bessant (2003)	A	UK	Presented enablers and strategic blockages in pursuing mass customization via mapping process.	Conceptual and Empirical	International Journal of Operations and Production Management	Car and Computer industries

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115	Coronado (2003)	A	UK	Proposed a framework that ensures Information System is providing benefits to Manufacturing industries.	Empirical	Industrial Management and Data Systems	SMEs
116	Crocitto and Youssef (2003)	A	USA	Presented a model of agility based on suppliers, organizational members and customers united through information technology.	Descriptive	Industrial Management and Data Systems	-
117	Jackson and Johanssson (2003)	A	Sweden	Presented an investigation into the concept of agility and how it can be applied within industry.	Empirical	Integrated Manufacturing Systems	-
118	Jiang and Fung (2003)	A	China	Proposed an infrastructure for adaptive production control in AM environment - Virtual Production System (VPS).	Descriptive	International Journal of Manufacturing Technology	-
119	Jin-Hai *et al.* (2003)	A	China	Proposed a "Real AM" concept as a strategic process based on four fundamentals: benefit, integration, IT and core competency.	Conceptual	Business Process Management Journal	-
120	McCarthy and Tsinopoulos (2003)	A	UK	Proposed a strategic management framework based on configurational theory and an evolutionary classification method.	Descriptive	Integrated Manufacturing Systems	-
121	Moore *et al.* (2003)	A	UK	Presented a virtual manufacturing approach for designing, programming, testing, verifying and deploying control systems for agile modular manufacturing.	Descriptive	Mechatronics	-
122	Peças and Henriques (2003)	A	Portugal	Presented the management strategies and methodologies used to fully implement LM.	Empirical	Proceedings of the Business Excellence	Mould Industry
123	Prince and Kay (2003)	A	UK	Presented development of virtual group concept and its application in functional layouts.	Descriptive and Empirical	International Journal of Production Economics	Cables Industry
124	Rabelo (2003)	A	Brazil	Presented an implementation of framework dealing with high level of heterogeneity that a multi agent scheduling system should tackle.	Descriptive	International journal of computer applications in technology	-
125	Stratton and Warburton (2003)	A	UK	Explored the role of inventory and capacity in accommodating variation.	Descriptive and Empirical	International Journal of Production Economics	Apparel Industry

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126	Su *et al.* (2003)	A	China	Presented the problem of partner selection for Virtual Enterprises using Genetic Algorithm.	Descriptive	IEEE International Conference	-
127	Uribe *et al.* (2003)	A	Mexico	Presented a practical modelling technique for minimizing the required investment in capacity planning for discrete manufacturing under an uncertain demand stream.	Descriptive	International journal of Production Research	-
128	Wang *et al.* (2003)	A	China	A multi-agent and distributed ruler based approach to production scheduling in AM systems is proposed.	Descriptive	International Journal of Computer Integrated Manufacturing	-
129	Yao and Carlson (2003)	A	USA	Presented a study of production system implementing MRP, JIT and TQM in a complex and demanding environment of furniture production.	Descriptive and Empirical	International Journal of Production Economics	Furniture manufacturing
130	Yusuf *et al.* (2003)	A	UK	Presented an empirical study about the benefits of implementation of AM.	Empirical	Management Decision	-
131	Zhang *et al.* (2003)	A	Hong Kong	A new application integration platform for an AM environment is presented, based on agent and Common Request Broker Architecture (CORBA).	Descriptive	International journal of Advanced Manufacturing Technology	-
132	Zhou *et al.* (2003)	A	China	Proposed a hybrid hierarchical model for agile job scheduling in virtual workshop environment.	Descriptive	International journal of Advanced Manufacturing Technology	-
133	Bruce *et al.* (2004)	A	UK	Discussed the characteristics of lean, agile and le-agility within existing SC literature.	Comparative	International Journal of Operations and Production Management	Textile and Clothing Industry
134	BüyüKözkan *et al.* (2004)	A	Turkey	Presented synergistic impact of new product development and concurrent engineering and to survey their methods and tools in association with AM.	Exploratory	Journal of Intelligent Manufacturing	-
135	Cagliano *et al.* (2004)	A	Italy	Presented supply strategies of European manufacturing firms.	Empirical	Journal of Purchasing and Supply Management	-

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136	Conboy and Fitzgerald (2004)	P	Ireland	Proposed to develop a comprehensive framework of software development agility, through a thorough review of agility across many disciplines.	Descriptive	ACM workshop on Interdisciplinary software engineering research	-
137	Coronado *et al.* (2004)	A	UK	Studied the agility in four SMEs in high-tech manufacturing industries and the impact made by information systems on agile performances.	Empirical	International Journal of Operations and Production Management	SMEs
138	Elkins *et al.* (2004)	P	USA	Discussed two decision models that provide initial insights and industry perspective into business case for investment in AM systems.	Comparative	International Journal of Production Economics	Automotive industry
139	Helo (2004)	A	Finland	Analyzed electronics manufacturing industry in the context of AM and proposed the data system implementations based on context requirements.	Empirical	Industrial Management and Data Systems	Electronics Manufacturing
140	Ip *et al.* (2004)	A	Hong Kong	Proposed a theory of solution space reduction which efficiently reduced the complexity of problems.	Descriptive	International journal of production research	-
141	Le *et al.* (2004)	A	Australia	Presented a production planning methodology that can be implemented robustly and quickly.	Descriptive	IEEE International Conference	-
142	Lee *et al.* (2004)	A	Hong Kong	Presented a dynamic data interchange scheme to exchange the data automatically and enable the filtering of valuable data.	Descriptive	International Journal of Production Economics	-
143	Li *et al.* (2004)	A	China	Presented a framework of AM Cell planning and validated using a case study.	Empirical	International journal of Manufacturing Technology	Mould Industry
144	Lin *et al.* (2004)	A	Taiwan	Addressed how to logically link the AM strategies and MIS requirements, using relationship matrices to integrate manufacturing information.	Empirical	IEEE International Conference	-
145	Yu and Krishnan (2004)	A	USA	Presented the architecture and cooperation mechanism of web-based AM cells.	Descriptive	Information Systems Journal	-
146	Yusuf *et al.* (2004)	A	UK	Presented emerging patterns in SC integration, and relationships between emerging patterns and attainment of competitive objectives.	Exploratory	European Journal of Operational Research	-

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147	Baker (2005)	P	USA	Described the journey of DTE Energy in realizing the agility and process improvements in Fortune 300 corporation.	Descriptive	Proceedings of the Agile Development Conference	IT Industry
148	Deshayes *et al.* (2005)	A	USA	Presented a mathematical and information framework for optimization of machining processes within a Smart Machining System (SMS).	Empirical	Proceedings of Mechanical Engineering Congress and Exposition	-
149	Devadasan *et al.* (2005)	A	India	Presented a modified orthogonal array-based model to exploit the DOE in AM.	Empirical	Journal of Manufacturing Technology Management	Pump industry
150	Erbe (2005)	A	Germany	Presented a framework for organizational learning in individual as well as networked enterprises under AM.	Descriptive	Integrating Human Aspects in Production Management	-
151	Gaafar and Masoud (2005)	A	Egypt	Proposed genetic algorithm and simulated annealing techniques for scheduling in AM.	Empirical	International Journal of Production Research	-
152	Raschke and David (2005)	A	USA	Defined operational agility and tested a conceptual model.	Empirical	Proceedings of Information Systems, Omaha, NE, USA	-
153	Wang *et al.* (2005)	A	China	Presented the assembly variant design system architecture and the assembly modelling methodology.	Descriptive	IIE Transactions	-
154	Yu *et al.* (2005)	A	Taiwan	Proposed a parametric manufacturing knowledge representation model to address the issue of product configuration variations and manufacturing agility and facilitate AM execution control.	Descriptive	Journal of the Chinese Institute of Industrial Engineers	-
155	Agarwal *et al.* (2006)	A	India	Proposed a framework for modelling performance of lean, agile and le-agile supply chain.	Empirical	European Journal of Operations Research.	FMCG
156	Bateman and Cheng (2006)	A	UK	Reviewed the various technologies, trends in Reconfigurable Manufacturing and discusses the approach and applications of RM to increase agility.	Empirical	International Journal of AM	-
157	Cao and Gao (2006)	A	China	Proposed a Penalty guided genetic algorithm to perform partner selection and risk control in AM.	Exploratory	Proceedings of World Congress on Intelligent Control and Automation	-

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158	Guo *et al.* (2006)	A	China	Proposed agent based systems and CORBA to enhance system integration across different platforms to support AM.	Descriptive	International Conference on Machine Learning and Cybernetics, Dalian	-
159	Ismail and Sharifi (2006)	A	UK	Proposed a framework for development of ASC based on integration of SCD and DSC.	Descriptive	International Journal of Physical Distribution and Logistics Management.	-
160	Ismail *et al.* (2006)	A	UK	Presented a framework for implementation of AM.	Descriptive	International Journal of Agile Systems and Management	SMEs
161	Leitão and Restivo (2006)	A	Portugal	Presented an agile and adaptive manufacturing control architecture that uses adaptive control.	Descriptive	Computers in Industry	-
162	Lin *et al.* (2006)	A	Taiwan	Presented the development of absolute agility index using fuzzy logic to address ambiguity in agility evaluation.	Empirical	International Journal of Production Economics	-
163	Monostori *et al.* (2006)	A	Hungary	Presented applications of software agents and multi-agent systems and study of potential manufacturing applications.	Exploratory	CIRP Annals - Manufacturing Technology	-
164	Narasimhan *et al.* (2006)	A	USA	Presented a review of leanness and agility w.r.t. manufacturing paradigms and performance capabilities.	Exploratory	Journal of Operations Management	-
165	Poolton *et al.* (2006)	A	UK	Proposed to apply principles of AM to marketing strategy, planning and management for SMEs.	Empirical	Marketing Intelligence and Planning	SMEs
166	Rao *et al.* (2006)	A	China	Proposed an agent based control architecture for AMS using RMCs.	Empirical	International Journal of Production Research	-
167	Shu *et al.* (2006)	A	China	Proposed the conditions needed for integration of Agile Virtual Enterprises based Collaborative Planning and Forecasting Replenishment.	Descriptive	IEEE International Conference	-
168	Tanimizu *et al.* (2006)	A	Japan	Proposed a new evolutionary method to improve the performance of genetic algorithm based on reactive scheduling process.	Empirical	International Journal of Production Research	-

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169	Vázquez-Bustelo and Avella (2006)	A	Spain	Presented an initial approach to AM based on 4 case studies in Spanish industries.	Exploratory	Technovation	-
170	Viharos *et al.* (2006)	A	Hungary	Summarized ideas and results for AM with active disturbance handling approach for real-time manufacturing control.	Descriptive	World Congress Metrology for a Sustainable Development	-
171	Xing *et al.* (2006)	A	South Africa	Proposed reconfigurable manufacturing systems to achieve Mass Customization Manufacturing (MCM) leading to AM.	Descriptive	International Conference on CAD/CAM, Robotics and Factories of the Future	-
172	Aiello *et al.* (2007)	A	Italy	Proposed agile control system development (AGOCOSD) methodology for modelling and programming manufacturing control systems and Industrial trails are used to validate it.	Empirical	IEEE International Conference on Industrial Informatics	Low Volume and High Variety parts manufacturing firm
173	Anuziene and Bargelis (2007)	A	Lithuania	Developed framework of decision support system for AM of mechanical products.	Empirical	Proceedings of Mechanika 2007	Mechanical parts manufacturing firm
174	Chen *et al.* (2007)	A	USA	Proposed a new concept of interface management by reviewing two approaches - lean construction and agile project management.	Descriptive	Proceedings IGLC	Construction Industry
175	Deif and Elmaraghy (2007)	A	Canada	Developed a dynamic control approach for linking manufacturing strategy with market strategy through a reconfigurable manufacturing planning and control (MPC) system to support agility.	Descriptive and Empirical	Journal of Manufacturing Systems	Automatic PCB assembly factory
176	Gosling *et al.* (2007)	A	USA	Postulated the implementation of Lean and Agile practices in Construction industry and accrued benefits.	Empirical	Proceedings of International conference on AM	Construction Industry

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177	Hasan *et al.* (2007)	A	India	Explored various barriers to adopt AM and established a relationship among the dimensions of barriers through the interpretive structural modelling methodology.	Exploratory	International Journal of Agile Systems and Management	-
178	Hsu (2007)	A	USA	Presented the design of double sampling s-chart as an optimizing solution.	Empirical	Quality and Reliability Engineering International	-
179	Kamal *et al.* (2007)	A	USA	Demonstrated and analyzed agile method, that relies solely on simple single-sided tooling, to form open-box-like enclosures with surface detail.	Empirical	Journal of Materials Processing Technology	Manufacturing
180	Krishnamurthy and Yauch (2007)	A	USA	Proposed a theoretical model of le-AM as it applies to a single corporate enterprise with multiple business units	Exploratory	International Journal of Operations and Production Management	North America based production company
181	Ramesh and Devadasan (2007)	A	India	Reviewed the literature and contributed a comprehensive model that would identify the criteria for attaining agility.	Empirical	Journal of Manufacturing Technology Management	-
182	Sarkis *et al.* (2007)	A	USA	Provided a practical model usable by industries to form agile virtual enterprises.	Empirical	International Journal of Operations and Production Management	-
183	Sherehiy *et al.* (2007)	A	USA	Reviewed existing knowledge of AM and agile workforce, with a view to extend it to whole enterprise.	Empirical	International journal of Industrial Ergonomics	-
184	Vázquez-Bustelo *et al.* (2007)	A	Spain	Presented a conceptual model, based on the literature and a previous case study, to relate turbulence in the environment with AM practices and business performance.	Conceptual and Empirical	International Journal of Operations and Production Management	Spanish manufacturers
185	Yauch (2007)	A	USA	Analyzed team attributes necessary to facilitate AM using balance theory as a framework which evaluates the potential positive and negative impacts.	Empirical	Applied Ergonomics	-

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186	Zerenler (2007)	A	Turkey	Explored the role played by IT on business performance under AM.	Empirical	IEEE International conference	Textile Industry
187	Zhang and Sharifi (2007)	A	UK	Proposed a framework for the implementation of agility as a manufacturing strategy.	Exploratory	Engineering Management	UK manufacturing industries
188	Zhao *et al.* (2007)	A	USA	Presented overview of concepts in service computing leading to technological and managerial foundation for enterprise agility.	Empirical	Information Systems Frontiers	-
189	Calvo *et al.* (2008)	A	Spain	Formulated a systemic criterion of sustainability in AM and computed it's through flexibility and complexity.	Descriptive	International Journal of Production Research	-
190	Carlson and Yao (2008)	A	USA	Developed a simulation which generates expected outputs under conditions of operation variability, queue lengths and batch changeover times.	Empirical	International Journal of production economics	Furniture manufacturing
191	Chandna (2008)	A	India	Presented a fuzzy logic, knowledge-based framework for the assessment of manufacturing agility.	Descriptive	Proceedings of the World Congress on Engineering	-
192	Erande and Verma (2008)	A	USA	Described methodology used to develop comprehensive agility measurement tool using analytic hierarchy process.	Descriptive	International Journal of Applied Management and Technology	-
193	Fung *et al.* (2008)	A	China	Presented a multi-stage cell formation methodology, which can help select appropriate resources and form the Virtual Cell from AM.	Descriptive	International Journal of Advanced Manufacturing Technology	-
194	Garbie *et al.* (2008)	A	USA	Proposed a novel model to measure the agility level of the manufacturing firms.	Empirical	International Journal of Computer Applications in Technology	Air conditioners manufacturer
195	Hasan *et al.* (2008)	A	India	Designed and implemented a procedure for judging the suitability of suppliers for an organization competing on AM characteristics.	Descriptive and Empirical	International Journal of Logistics Systems and Management	Forging and Gear manufacturer
196	Kässi *et al.* (2008)	A	Finland	Identified how the product modular design can increase its offerings and allow the manufacturing process to reach economy in a quickly changing market.	Descriptive	Mechanika.-Kaunas: Technologija	-

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197	Liao and Liao (2008)	A	Taiwan	Addressed a manufacturing system that applies the assembly-driven differentiation strategy using ant colony optimization algorithm.	Descriptive	International Journal of Production Research	-
198	Su *et al.* (2008)	A	China	Discussed the details of comprehensive information platform for establishing a two-echelon supply chain.	Descriptive and Empirical	Intelligent Control and Automation	Garments Industry
199	Bottani (2009)	A	Italy	Explored the issues arising when attempting to quantitatively assess the agility level of a company.	Empirical	International Journal of Logistics: Research and Applications	Welded construction and metal structures sector
200	Brusaferri *et al.* (2009)	A	Italy	Described main steps of a structured control system development approach to the design of control and supervision systems of AM systems.	Descriptive	Emerging Technologies and Factory Automation	-
201	Hallgren and Olhager (2009)	A	Sweden	Investigated internal and external factors that drive the choice of lean and agile operations capabilities and their respective impact on operational performance.	Exploratory	International Journal of Operations and Production Management	Manufacturing firms in Europe, Asia, and North America
202	Hasan *et al.* (2009a)	A	India	Identified and determined a relationship among the various enablers for the AM philosophy.	Descriptive and Empirical	International Journal of Industrial and Systems Engineering	-
203	Hasan *et al.* (2009b)	A	India	Discussed about the formation Virtual Constituent Industries for implementing AM by using analytical network process and goal programming.	Empirical	International Journal of Operational Research	-
204	Hasan *et al.* (2009c)	A	India	Provided an insight into a selection method for production systems from amongst competing alternatives having varying degrees of tangible and intangible advantages and benefits.	Descriptive	International Journal of Manufacturing Technology and Management	-
205	Kettunen (2009)	P	Finland	Explored the commonalities between the key concepts of AM and some of the most popular agile software methods.	Comparative	Technovation	Software industry

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206	Luo *et al.* (2009)	A	China	Developed a model that helps to overcome the information-processing difficulties inherent in screening a large number of potential suppliers in the early stages of the selection process.	Empirical	Journal of Purchasing and Supply Management	Chinese electrical equipment manufacturing industries
207	Maciá-Pérez *et al.* (2009)	A	Spain	Proposed a process management system that enables new dynamic manufacturing models to be implemented.	Empirical	Enterprise Distributed Object Computing Conference Workshops	-
208	Nambiar (2009)	A	USA	Proposed a taxonomic framework by integrating lean principles and mass customization for the implementation of AM.	Empirical	Computers and Industrial Engineering	-
209	Pandey and Garg (2009)	A	India	Identified various enablers used by researchers and practitioners for flexibility, integration and responsiveness to customer's needs.	Descriptive	Journal of advances in management research	Indian manufacturing industries
210	Vinodh *et al.* (2009a)	A	India	Presented that computer-aided design of experiments would facilitate time compression and enhance accuracy, which is a major enablers of achieving AM.	Empirical and Exploratory	International Journal of Advanced Manufacturing Technology	Rotary Switch industry
211	Vinodh *et al.* (2009b)	A	India	Explored the researches reported in literature on AM and determined the avenues by which agility can be imparted in traditional sectors	Empirical	Industrial Management and Data Systems	-
212	Vinodh *et al.* (2009c)	A	India	Proposed a system called total agile design system which helps an organization to design its products, processes and services to achieve agility.	Empirical	International Journal of Production Research	-
213	Wang (2009)	A	Taiwan	Proposed manufacturing agility evaluation approach based on concepts of TOPSIS by analyzing the agility of organization.	Descriptive	Expert Systems with Applications	
214	Wang and Lin (2009)	A	Taiwan	Proposed the application of radio frequency identification technique and multi-agent system in developing an agent-based AM planning and control system.	Descriptive	Computers and Industrial Engineering	-

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215	Almahamid *et al.* (2010)	A	Jordan	Investigated the role of agile capabilities and knowledge sharing practices in gaining competitive advantage in manufacturing industries in Jordan.	Exploratory	International Journal of Management	Manufacturing industries in Jordan
216	Ayyappan and Jayadev (2010)	A	India	Presented the AM enabling technologies and implementation framework to develop a variety of products at low cost and in a short period.	Conceptual	IUP Journal of Operations Management	-
217	Bottani (2010)	A	Italy	Investigated both the profile of agile industries and the enablers practically adopted by industries to achieve agility.	Exploratory	International Journal of Production Economics	Small and medium enterprises
218	Huang and Li (2010)	A	Taiwan	Presented a study of how an OEM can become le-agile by reengineering its supply chain.	Descriptive and Empirical	Journal of Manufacturing Systems	PC industry
219	Jassbi *et al.* (2010)	A	Iran	Developed a new approach based on adaptive neuro fuzzy inference system for evaluating agility in supply chain.	Empirical	International Journal of Industrial Engineering and Production Research	Car manufacturing company in Iran
220	Loforte and Timóteo (2010)	A	Portugal	Presented a model to prioritize available management systems and to help small to medium-sized enterprises address the challenge of today's market competition more effectively.	Empirical	Journal of Enterprise Information Management	Small to medium-sized enterprises (SMEs)
221	Lu and Tseng (2010)	A	China	Proposed an efficient and systematic methodology for developing an object-oriented AM control system.	Descriptive	International Journal of Advanced Manufacturing Technology	-
222	Pan and Nagi (2010)	A	USA	Analyzed a supply chain design problem for a new market opportunity with uncertain demand in an AM setting.	Descriptive	Computers and Operations Research	Semiconductor manufacturing and automotive manufacturing.
223	Puik and van (2010)	A	Netherland	Benchmarked equiplet production for reducing time to market and a smooth transition from research and development to manufacturing.	Descriptive	Precision Assembly Technologies and Systems	Traditional micro assembly
224	Serugendo and Frei (2010)	A	UK	Described how a development method for self-organizing systems provides solutions to user-friendly AM systems.	Descriptive	International Conference on Self-Adaptive and Self-Organizing Systems	-

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225	Van *et al.* (2010)	A	Netherland	Developed an agent-based software infrastructure for agile industrial manufacturing of micro devices.	Empirical	Conference ASME	-
226	Vinodh *et al.* (2010a)	A	India	Proposed a model for enabling organizations to improve their agility level and used fuzzy ANP to enable the selection of best concept.	Empirical	International Journal of Production Research	Indian traditional manufacturing organisation
227	Vinodh *et al.* (2010b)	A	India	Achieved agile product development through the interfacing of computer aided design and rapid prototyping technologies.	Descriptive and Empirical	International Journal of Advanced Manufacturing Technology	Pump industry
228	Vinodh *et al.* (2010c)	A	India	Indicated the need of amalgamating mass customization and AM principles for achieving competitiveness in organizations.	Descriptive	International Journal of Production Research	-
229	Vinodh *et al.* (2010d)	A	India	Carried out research to assess the agility level of an organization using an agility index measurement model.	Empirical	International Journal of Production Research	-
230	Vinodh *et al.* (2010e)	A	India	Proposed a model called total agile design system which is a scoring model for measuring agility before and after implementation.	Descriptive	International Journal of Advanced Manufacturing Technology	Traditional manufacturing organisation
231	Catalán *et al.* (2011)	A	Spain	Presented the COSME platform for the distributed control of communicating machine tools in the context of AM Systems.	Descriptive	Emerging Technologies and Factory Automation	-
232	Inman *et al.* (2011)	A	USA	Tested a structural model incorporating AM as the focal construct.	Exploratory	Journal of Operations Management	-
233	Ismail *et al.* (2011)	A	UK	Described a practical ‘top-down’ strategic framework to assist manufacturing-based SMEs to develop a degree of resilience.	Descriptive and Empirical	International Journal of Production Research	SMEs
234	Madureira *et al.* (2011)	A	Portugal	Addressed the development of self-organization methods to enhance the operations of a scheduling system.	Descriptive	Cybernetic Intelligent Systems	-

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235	Mashayekhi *et al.* (2011)	A	Iran	Reviewed the literature in the field of AM and offered a model of agility based on leadership, human resource, organizational structure, organizational culture, process and system in the organization.	Empirical	International Journal of Industrial Engineering	Iranian industrial organization
236	Tseng and Lin (2011)	A	Taiwan	Suggested a new agility development method for dealing with the interface and alignment issues among the agility drivers, and capabilities.	Descriptive and Empirical	Information Sciences	Taiwanese information technology
237	Vinodh (2011)	A	India	Reported an axiomatic model of agile production system design using process variables.	Descriptive and Empirical	International Journal of Production Research	Indian electronic switches manufacturer
238	Vinodh and Chintha (2011)	A	India	Reported the research in which a fuzzy quality function deployment approach has been used for enhancing agility improvement of a traditional manufacturing organization.	Exploratory	The TQM Journal	Rotary switches manufacturing organization
239	Vinodh and Devadasan (2011)	A	India	Carried out research to assess the agility level of an organization using fuzzy logic approach.	Exploratory	The International Journal of Advanced Manufacturing Technology	Manufacturing organisation
240	Vinodh and Kuttalingam (2011)	P	India	Suggested the use of CAD and CAE for enabling product development in AM practices.	Empirical	Journal of Manufacturing Technology Management	-
241	Vinodh and Prasanna (2011)	A	India	Used multi-grade fuzzy approach for the evaluation of agility in the supply chain.	Empirical	International Journal of Production Research	Switch manufacturing industry
242	Zandi and Tavana (2011)	A	Iran	Presented a novel structured approach to evaluate and select the best agile e-CRM framework in a rapidly changing manufacturing environment.	Descriptive and Empirical	Computers and Industrial Engineering	-
243	Zhang (2011)	A	UK	Developed a numerical taxonomy of AM strategies based on a large scale questionnaire study of UK industry.	Empirical	International Journal of Production Economics	UK based industry

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
244	AL-Tahat and Bataineh (2012)	A	Jordan	Mapped various tactics of AM in different production areas.	Descriptive and Exploratory	Mathematical Problems in Engineering	-
245	Beck (2012)	A	USA	Reviewed the literature and investigated some attractive features of the border region using proximity-based model interspersed with the components of AM.	Empirical	International Business and Economics Research Journal	-
246	Browaeys and Fisser (2012)	A	Netherland	Presented an alternative approach to the concepts of lean and agile, using an epistemological point-of-view.	Comparative	The Learning Organization	-
247	Castro *et al.* (2012)	A	Portugal	Analyzed international and national research and development programs and roadmaps for agile and LM sector.	Exploratory	The Learning Organization	-
248	Costantino *et al.* (2012)	A	Italy	Addressed the configuration problem of Manufacturing Supply Chains (MSC) with reference to the supply planning issue.	Empirical	International Journal of Production Economics	Manufacturing
249	Denning (2012)	P	USA	Identified what customers want, how to deliver features of products that meet the tests.	Conceptual and Empirical	Strategy and Leadership	-
250	Fathizadeh *et al.* (2012)	A	Iran	Made a survey to study the relationship between organizational structure and organizational agility in an insurance company in Iran.	Exploratory	Management Science Letters	Insurance company
251	Flumerfelt *et al.* (2012)	A	USA	Perused the theories and practices of agile and LM systems to determine whether they employ sustainability, complexity and organizational learning.	Comparative	The Learning Organization	-
252	Frei and Whitacre (2012)	A	UK	Described an important mechanism by which biological systems can cope with uncertainty through properties described as degeneracy and networked buffering.	Descriptive	Natural Computing	
253	Fu *et al.* (2012)	A	USA	Developed a novel methodology for the design of a flexible super Water-reuse network design (WRND) based on different manufacturing purposes.	Empirical	Computers and Chemical Engineering	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
254	Hasan *et al.* (2012)	A	India	Provided insights into a decision aid for evaluating production flow layouts that support and enhance the agile manufacture of products.	Descriptive	Computers and Industrial Engineering	-
255	Hasani *et al.* (2012)	A	Iran	Proposed a comprehensive model for strategic closed-loop supply chain network design under interval data uncertainty.	Empirical	International Journal of Production Research	Food and high-tech electronics manufacturing industries
256	Houyou *et al.* (2012)	P	Germany	Described the potential impact of the Internet of Things (IoT) technologies and architecture on factory automation.	Descriptive	Emerging Technologies and Factory Automation	Factory Automation
257	Maciá *et al.* (2012)	A	Spain	Proposed a new paradigm call as Cloud AM based on Business Process Management (BPM), Cloud Computing, Service Oriented Architectures (SOA) and Ontologies.	Descriptive	International Journal of Advanced Science and Technology	-
258	Oyedijo (2012)	A	Nigeria	Examined the relationship between strategic agility and competitive performance using data generated from nine firms in Nigeria's telecommunication industry.	Exploratory	Business and Management Review	Nigeria's telecommunication industry
259	Pires *et al.* (2012)	A	Portugal	Identified the main limitations and shortcomings in the analysis of the resource selection process in Agile and Virtual Enterprises.	Exploratory	Journal of applied research and technology	-
260	Putnik (2012)	A	Portugal	Presented an analysis of the special issue on "lean vs agile", contributing to the higher levels of the theories of "lean" and "agile".	Conceptual and Exploratory	The Learning Organization	-
261	Putnik and Putnik (2012)	A	Portugal	Presented the argumentation on "lean" and "agile" as exclusive concepts and their analysis through the CST lenses.	Comparative	The Learning Organization	-
262	Rajan *et al.* (2012)	A	India	Implemented AM principle in designing of pump with an objective to reduce the lead time, weight and cost of the pump.	Empirical	International Journal of Emerging Technology and Advanced Engineering	Pump manufacturing sector
263	Van *et al.* (2012)	A	Netherland	Developed an agent-based software infrastructure for agile industrial production.	Exploratory	Intelligence and Intelligent Agent Technology	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
264	Vinodh and Aravindraj (2012)	A	India	Evaluated the current agile position of the firm using IF–THEN rules approach in an Indian modular switches manufacturing company.	Empirical	International Journal of Production Research	Indian modular switches manufacturing company
265	Vinodh *et al.* (2012a)	A	India	Created an AM model and used structural equation modelling method to validate the model.	Exploratory	International Journal of Production Research	Automotive Industry
266	Vinodh *et al.* (2012b)	A	India	Developed a method for agility assessment of an Indian electric automotive car manufacturing organization using an effective multi-grade fuzzy method.	Exploratory	International Journal of Production Research	Indian electric automotive car manufacturing organisation
267	Vinodh *et al.* (2012c)	A	India	Assessed the agility of the pump manufacturing organization using a scoring approach.	Empirical	International Journal of Advanced Manufacturing Technology	Pump manufacturing organisation
268	Weng and Jenq (2012)	A	Taiwan	Used the basis of axiomatic design and customer requirements to build a hierarchical decision-making model for equipment selection in AM units.	Empirical	International Journal of Advanced Manufacturing Technology	Production Organization
269	Aravind *et al.* (2013)	P	India	Applied graph theory for conceptual modelling the agile system and computed the dependencies among the individual agile enabler, criteria and attributes.	Empirical	International Journal of Production Research	Indian automotive component manufacturing organisation
270	Chang *et al.* (2013)	A	Taiwan	Established a hybrid approach for discovering the critical agility factors when launching a new product into mass production.	Empirical	International Journal of Production Research	-
271	Drake *et al.* (2013)	A	UK	Presented a purchasing portfolio model for determining purchasing strategy at the component level of a product to support business strategy.	Empirical	Supply Chain Management: An International Journal	Electric boiler manufacturer and elevator manufacturer in South Korea
272	Elmoselhy (2013)	A	Netherland	Explained the sources of competitive advantage in automotive industry by adopting the technical facet of the hybrid lean–AM system.	Descriptive	Journal of Manufacturing Systems	Automotive sector

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
273	Gharakhani *et al.* (2013)	A	Iran	Discussed the trade-off between AM, lean production, just in time systems and products quality improvement.	Comparative	Life Science Journal	Automotive industry
274	Goriwondo *et al.* (2013)	A	Zimbabwe	Established the level of agility that exists in Zimbabwean manufacturing industries and proposed an AM model for them.	Empirical	China-USA Business Review	Manufacturing industry in Zimbabwe
275	Grimheden (2013)	A	Sweden	Studied the integration of agile methods into mechatronics design.	Empirical	Mechatronics	Education Industry
276	Hannola *et al.* (2013)	A	Finland	Analyzed the applicability of agile methods for improving the efficiency of the innovation process.	Empirical	International Journal of Business Innovation and Research	Software Development
277	Lalmazloumian *et al.* (2013)	A	Malaysia	Developed a multi-product, multi-period, multi-echelon robust mixed-integer linear programming model with the objective of minimizing the influence of uncertain parameters and variables.	Empirical	Annals of Operations Research	-
278	Lotfi *et al.* (2013)	A	UK	Identified factors that can help firms to achieve resilience and answered the questions regarding how resilience fits with leanness and agility.	Exploratory	Proceedings of Production and Operations Management Society	Manufacturing industry in Germany
279	Meier *et al.* (2013)	A	Germany	Proposed an Industrial Product-Service System (IPS) Control Architecture for the operation phase.	Descriptive	Procedia CIRP	-
280	Mishra *et al.* (2013)	A	India	Developed an agility evaluation approach to determine the most suitable agile system for implementing mass customization strategies.	Descriptive	Benchmarking: An International Journal	-
281	Muduli (2013)	A	India	Addressed the research gap of the attributes of an agile workforce and identified the management practices capable of promoting workforce agility.	Empirical	IUP Journal of Management Research	-
282	Onofrejová and Kováč (2013)	A	Slovakia	Developed a framework of AM, especially reconfigurable manufacturing systems and their projection according to the current scientific research.	Descriptive	Transfer inovácií	-

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
283	Telgen *et al.* (2013a)	A	Netherland	Presented a case study on flexible and hybrid software architecture, which uses self-configurable manufacturing machines called equiplet.	Empirical	Proceedings Intelli 2013	Software technology
284	Telgen *et al.* (2013b)	A	Netherland	Introduced the concept Grid Manufacturing and an architecture where the control of the manufacturing is abstracted from the product manufacturing blueprint.	Descriptive	IEEE International Conference	-
285	Vinodh and Aravindraj (2013)	A	India	Presented a conceptual model of le-agility imbibed with lean and agile principles.	Empirical	International Journal of Production Research	Indian transformer manufacturing organisation
286	Vinodh *et al.* (2013)	A	India	Developed a model for concept selection in the context of AM using fuzzy VIKOR model and compared with fuzzy TOPSIS methodology.	Empirical	International Journal of Advanced Manufacturing Technology	Rotary switch manufacturing organisation
287	Yang *et al.* (2013)	P	France	Developed an agile robotic solution called as REMORA for performing manufacturing tasks in aeronautic industries.	Descriptive	Robotics in Smart Manufacturing	Robotic Industry
288	Balakirsky and Kootbally (2014)	A	USA	Developed a knowledge-driven system that provides added agility by detecting and correcting action failures of robots.	Empirical	Robot Intelligence Technology and Applications	Robotic Industry
289	Balakirsky (2015)	A	USA	Developed a novel knowledge-driven system that provides added agility by removing the programming burden for new activities from the robot.	Empirical	Robotics and Computer-Integrated Manufacturing	Robotic Industry
290	Dubey and Gunasekaran (2015)	A	India	Presented a literature review to develop AM framework.	Empirical	International Journal of Advanced Manufacturing Technology	-
291	Rauch *et al.* (2015)	A	Italy	Discussed the need for new and innovative JIT solutions for construction industry.	Descriptive	Applied mechanics and materials	Construction Industry
292	Routroy *et al.* (2015)	A	India	Determined the agility level of a manufacturing system along different timelines using Fuzzy AM Index (FAMI) method	Empirical	Measuring Business Excellence	Indian manufacturing organization

S.No.	Author(s)	Profile of Author (s)	Country	Contribution to Research	Methodology	Journal Name	Type of Industry
293	Sekar *et al.* (2015)	A	India	Developed a comprehensive model for fitness evaluation and determined fitness index using fuzzy methods.	Empirical	Journal of Manufacturing Technology Management	Indian pump manufacturing company
294	Sindhwani and Malhotra (2015)	A	India	Identified the barriers of Lean and AM.	Comparative	International Journal of Advance Research and Innovation	-
295	Thilak *et al.* (2015)	A	India	Reviewed the literature to trace the origin of AM, identified its enablers, applications and the implementation of AM in the pump industry.	Empirical	The Scientific World Journal	Pump Industry
296	Leite and Braz (2016)	A	Portugal	Studied the principles of AM and the elements that define it like drivers, enablers and performance objectives.	Empirical	Journal of Manufacturing Technology Management	Mechanical equipment design
297	Najrani (2016)	A	USA	Explained three types of agility strategies - Reactive agility, Proactive agility and innovative agility.	Conceptual	Strategic Direction	-
298	Sharif *et al.* (2016)	A	Pakistan	Identified the gaps and enablers in exploring AM concepts in SMEs.	Empirical	Quiad-e-awam University Research Journal of Engg, Science and Technology	Manufacturing
299	Sindhwani and Malhotra (2016a)	A	India	Identified and analyzed the attributes that not only influence the implementation process but also each other.	Exploratory	International Journal of Process Management And Benchmarking	Manufacturing
300	Sindhwani and Malhotra (2016b)	A	India	Identified the factors necessary to implement AMS and reviewed the introduction of AMS using ISM/MICMAC.	Empirical	International Journal of Systems Assurance Engineering	Manufacturing

2.2.1 Review Methodology

The purpose of the literature review is to bring together and analyse significant amount of information on a particular topic. These days, the most economic and effective way to carry out the research is through the use of internet and various scholarly databases. However, in the internet the information is non-authenticated, non-reliable and non-effective. Therefore, Google Scholar is used to start the search for quality research paper. Initially “agile manufacturing” and “agility” were used as keywords to search the research papers. After going through some twenty five research papers which are having the keyword “agile manufacturing” and are most cited according to Google scholar database, some other keywords like “AM enablers”, “AM impediments”, “AM outcomes”, “AM literature review”, and “AM performance measurement” were identified. It is also noticed that in some of the papers the term “agility” indicates responsiveness but the research papers are not connected to AM. All the relevant research papers were downloaded in a year wise manner starting from the current year until there was no paper in Google scholar database or when AM was coined. On the AM literature review, around fifteen research papers were found. These papers were studied to find out previous research time span and area most researched in AM. Some of the research papers were also taken from the cross references of the literature review published in this particular field due to their influential role in the development of AM. After the first iteration, there were around 450 research papers having the searched keyword from 2016 to 1993. In the second iteration, the abstract of all the research papers were studied and the most relevant research papers were selected having good contribution towards the development and implementation of AM. In this iteration, some of the papers were found to be related to agile supply chain. These papers were excluded from research scope in order to keep our literature review more specific to AM. Some of the papers were also excluded which were found to be from not so reliable journals and conferences. Only research papers from the reputed journals and international conferences were selected in our study. The numbers of research papers were now reduced to three hundred.

There exist some limitations in the search methodology. The non-availability of complete access to some of the research articles compels us to exclude those research papers. However, the primary databases searched for the research papers were Emerald, Elsevier, Taylor and Francis, IEEE, Springer, Research Gate and Inderscience Publishing Groups. We wish to make it clear that all the research papers reviewed may not have the searched by the keywords and all the research papers having the searched keywords may have not been reviewed.

2.2.2 Descriptive Analysis of the Data

Some of the observations, results, and discussion based on the literature review are presented in this section.

Research methodology: The scholarly articles were classified into different types (i.e. descriptive, empirical, exploratory, comparative and conceptual) and its combination. The meaning of these research methodologies are given below:

Conceptual: Review deals with basic and fundamental concepts of AM.

Descriptive: Review deals with explanation and/ or description of AM content or process, performance measurement

Empirical: Review deals with data for study been taken from existing database, review, case study, taxonomy or typological approaches.

Comparative: Review deals with comparison between two or more practices or solutions and evaluation of the best practice or solution.

Exploratory: Where the object of study is to better analyse using surveys, in which information is collected at some point of time or over a duration of time from one or more locations.

Combinational: Reviews that reflect the combination of two or more methodologies.

Table 2.3 presents different research methodologies used by various researchers in their scholarly article. From the table, it is clear that about one third of the researchers have performed descriptive analysis and about one fourth of the researchers have relied on empirical analysis. A lot of importance is being given towards the AM performance measurement and process analysis through the descriptive and empirical analysis. Researchers have also put their focus on the real time case studies in different industries to analyse the available data for deciding the future goals of the industries. Combinations of two methodologies are also used by researchers to test some hypothesis pertaining to AM. It is evident from the table that literature review on AM is neglected by the researchers.

Table 2.3: Research methodologies in AM literature

S.No.	Methodology	No. of references	%
1	Descriptive	121	40.33
2	Empirical	84	28.00
3	Exploratory	26	8.67
4	Descriptive and Empirical	21	7.00
5	Comparative	17	5.67
6	Conceptual	16	5.33
7	Conceptual and Descriptive	4	1.33
8	Conceptual and Empirical	4	1.33
9	Empirical and Exploratory	2	0.67
10	Comparative and Empirical	1	0.33
11	Conceptual and Exploratory	1	0.33
12	Conceptual and Review	1	0.33
13	Descriptive and Exploratory	1	0.33
14	Empirical and Descriptive	1	0.33
	Total	**300**	**100**

Distribution of research papers over regional basis

Figure 2.1 shows the country wise distribution of reviewed papers. It is apparent from the figure that more research has been undertaken in USA, UK, India and China in the area of AM.

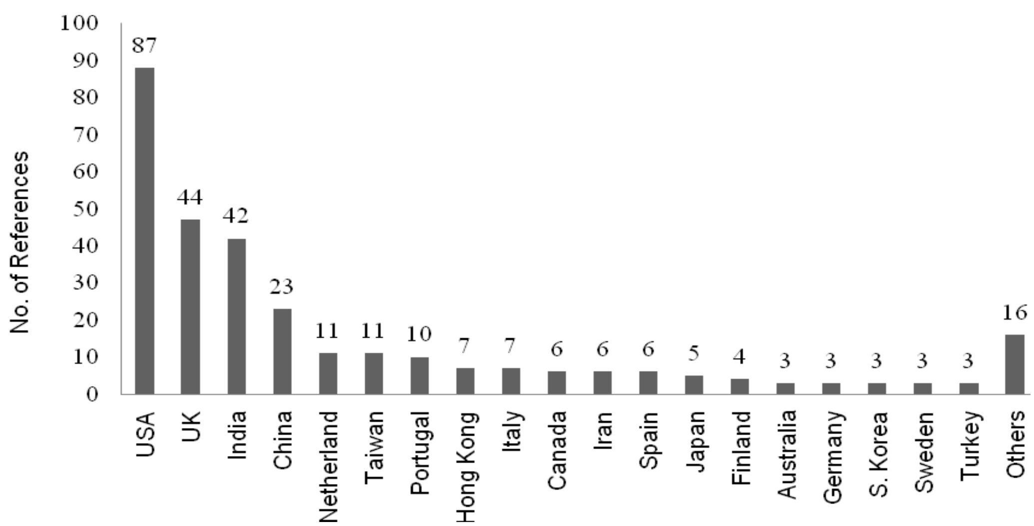

Figure 2.1: Number of research paper published by researchers from different countries (as per first author)

Obviously, these nations are developed or developing nations with very competitive businesses environment. Both academicians and practitioners in these nations have contributed to research in AM. Even though some of the developing nations have not produced literature, in all likelihood, it could mean that they could have collaborated and benefited from the research done by the developed nations

Distribution of author profile:

The major chunks of papers reviewed are from academicians amounting to approximately 92% (see Figure 2.2). This clearly states that there is a lot of academic interest and research in the field of AM. The observations point out that more number of academicians has contributed their findings as papers while a few personnel from industry have attempted to contribute to the literature. This could be because more emphasis is given to implantation of AM and less importance given to publication of papers among the industry personnel. In practical scenario, many of the industries are found to be experimenting and implementing the concepts of AM and that academicians have been working in close collaboration with the industry to test their ideas and implement their frameworks.

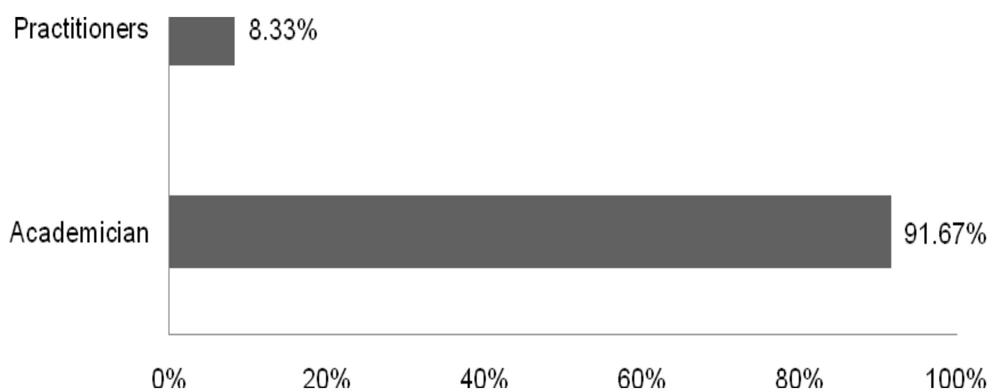

Figure 2.2: Distribution of author profile

Distribution of papers according to journals and conferences:

Table 2.3 shows the distribution of papers based on journals. The reviewed papers are a good mixture of reputed journals, conferences, workshops and IEEE transactions. For the ease of representation and analysis, the listing of conferences has been made into IEEE and others. Major chunk of the papers reviewed have come from international journals of repute like IJPR, IJPE, IJOPM, IJAMS etc. Those journals with less than three papers have been grouped as those with one paper and those with two papers for representation purpose. The fact apparent from the table is that AM has been a subject of research across the spectrum of journals. Papers have been published in journals from Manufacturing, Production Management, Operations management, Quality, Business excellence etc. This shows that AM has much to offer in every domain related to manufacturing to software and businesses. There are implicit advantages to be derived through the agile concepts.

Table 2.4: Distribution of papers according to journals and conferences

Journal Name	**Number of references**	**%**
International Journal of Production Research	31	10.53
IIE Transactions	28	9.21
International Journal of Production Economics	17	6.25
International Journal of Operations and Production Management	11	3.62
International Journal of Advanced Manufacturing Technology	10	3.29
International Journal of Agile Management Systems	9	2.96
Computers and Industrial Engineering	6	1.97
The International Journal of Advanced Manufacturing Technology	6	1.97
Industrial Management and Data Systems	5	1.64
Integrated Manufacturing Systems	5	1.64
Journal of Manufacturing Technology Management	5	1.64
The Learning Organization	5	1.64
Journal of Manufacturing Systems	4	1.32
Journal of Materials Processing Technology	4	1.32
Emerging Technologies and Factory Automation	3	0.99
Industrial Technology Institute	3	0.99
International Journal of Manufacturing Technology and Management	3	0.99
International Conference	32	10.53
Other Journals (2 each)	31	10.53
Other Journals (1 each)	82	26.97
Total	**300**	**100.00**

Distribution of papers over time:

The Figure 2.4 shows the distribution of reviewed papers according to the year of publication. The year wise pattern in publication of papers signifies that, during the initial period of conception of AM, the number of papers were very few (between 1993 to 1995) as the concept of AM was new and industry was fascinated and confident about LM. Gradually as the manufacturing paradigm shifted over to being able to operate in unpredictable environment, the concept of AM was given its due importance. The number of papers rose up steadily from 1996 to 2012, wherein many conceptual and empirical researches had been done to fine tune the AM philosophy and there has been widespread adoption in the industry. More research has been done on continuous basis by incorporating new features of analysing the AM environment using statistical, fuzzy and other techniques to come up with more sophistication, agility and flexibility.

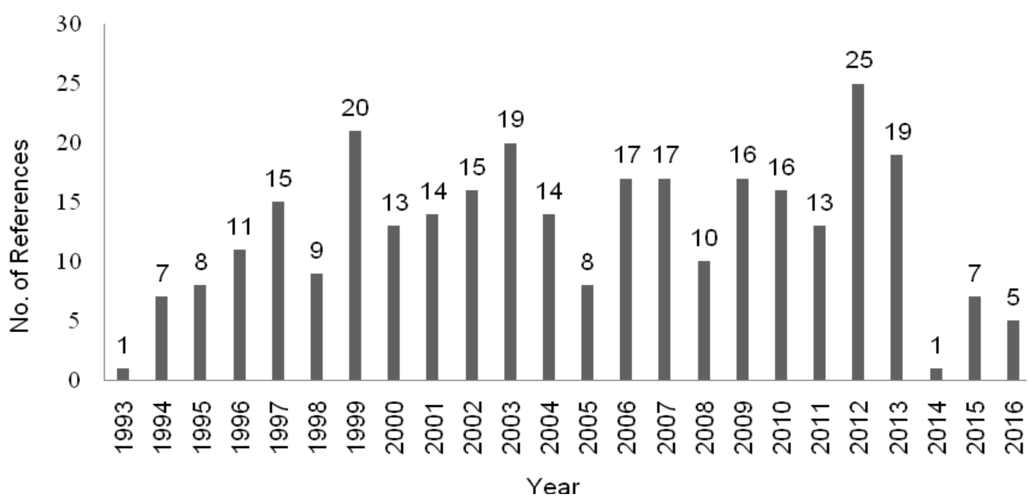

Figure 2.4: Year wise distribution of reviewed paper

Distribution of paper by type of industries:

The Table 2.5 shows industry wise listing of reviewed papers. It is observed that manufacturing and automotive industry has been taken as a basis for defining and developing the concepts and frameworks of AM. Automotive, electronic goods manufacturing and SMEs are industries striving for agility as these industries suffer from abrupt changes in customer preferences due to high-mix and low volume products. Maximum numbers of papers are devoted to manufacturing as they form the crux of major industries. Moreover some of the reviewed papers have not clearly defined the type of manufacturing industry and hence have been tabulated under manufacturing industry category. Textile/Clothing/Footwear is an industry that would largely benefit from the AM due to high degree of volatility in customer preferences and changes in designs; and few researchers have highlighted it in their papers. Moreover, papers from other domains like furniture, casting/moulding, education, insurance and telecom have shown the possible scope for further research in these domains. Other industries like Aerospace, Construction, Electrical and Electronics, Furniture, pumps, software, textile/clothing/Footwear industries are in the process of exploring the new manufacturing paradigm. These are the industries that are feeling the wrath of uncompromising customer demands for quality and cost. The trend in the table reflects the desire to adopt AM and more research can be undertaken in these domains for fruitful results to accrue.

Table 2.5: Distribution of references by industry sector

Type of Industry	Citations
Manufacturing Industry	Pandey and Garg (2009), Routroy *et al.* (2015), Vinodh and Aravindraj (2012), Vinodh *et al.* (2010a), Vinodh and Aravindraj (2013), Mashayekhi *et al.* (2011), Aiello *et al.* (2007), Sindhwani and Malhotra (2016a), Wang *et al.* (1996), Iyer and Nagi (1997), Kamal *et al.* (2007), Costantino *et al.* (2012), Sharif *et al.* (2016), Sindhwani and Malhotra (2016b), AlMahamid *et al.* (2010), Hallgren and Olhager (2009), Houyou *et al.* (2012), Hasani *et al.* (2012), Hasan *et al.* (2008), Aravind *et al.* (2013), Quintana (1998), Power *et al.* (2001), Lotfi *et al.* (2013), Goriwondo *et al.* (2013), Vinodh and Devadasan (2011), Minis *et al.* (1996), Leite and Braz (2016), Quinn *et al.* (1997), Anuziene and Bargelis (2007), Krishnamurthy and Yauch (2007), Weng and Jenq (2012), Cheng et al. (1998), Vinodh *et al.* (2013), Vinodh and Chintha (2011), Vinodh *et al.* (2009a), Pan and Nagi (2010), Zhang (2011), Vázquez-Bustelo*et al.* (2007), Vinodh and Prasanna (2011), Vinodh *et al.* (2010e), Puik and van (2010), Zhang and Sharifi (2007)
Automotive Industry	Vinodh *et al.* (2012b), Parunak (1995), Shen (1996), Elkins *et al.* (2004), Gharakhani *et al.* (2013), Elmoselhy (2013), Brown and Bessant (2003), Jassbi *et al.* (2010), Frayret *et al.* (2001)
Electronics Manufacturing	Deif and ElMaraghy (2007), Cho *et al.* (1996), Sanderson *et al.* (1994), Graves *et al.* (1996), Helo (2004), Vinodh (2011)
Small to medium-sized enterprises (SMEs)	Bottani (2010), Loforte and Timóteo (2010), Coronado (2003), Coronado *et al.* (2004), Ismail *et al.* (2006), Poolton *et al.* (2006), Ismail *et al.* (2011)
Pump Industry	Sekar *et al.* (2015), Devadasan *et al.* (2005), Vinodh *et al.* (2010b), Thilak *et al.* (2015), Vinodh *et al.* (2012c), Rajan *et al.* (2012)
Software industry	Tseng and Lin (2011), Huang and Li (2010), Baker (2005), Hannola *et al.* (2013), Kettunen (2009), Telgen *et al.* (2013a)
TCF (Textiles/Clothing/Footwear)	Stratton and Warburton (2003), Su *et al.* (2008), Sohal (1999),Bruce *et al.* (2004), Zerenler (2007)
Construction Industry	Chen *et al.* (2007), Gosling *et al.* (2007), Rauch *et al.* (2015), Bottani (2009)
Electrical appliance manufacturing industries	Luo *et al.* (2009), Drake *et al.* (2013), Lee and Lau (1999)
Robotic Industry	Yang *et al.* (2013), Balakirsky and Kootbally (2014), Balakirsky (2015)
Aerospace Industry	Richards (1996), Phillips (1999)
Cables and Conduit Industry	Prince and Kay (2003), Meade and Rogers (1997)

Type of Industry	Citations
Furniture manufacturing	Yao and Carlson (2003), Carlson and Yao (2008)
Mold Industry	Peças and Henriques (2003), Li *et al.* (2004)
Air conditioners manufacturer	Garbie *et al.* (2008)
Casting industry	Yang an Li (2002)
Education Industry	Grimheden (2013)
FMCG	Agarwal *et al.* (2006)
Food industry	Christian and Zimmers (1999)
Insurance company	Fathizadeh *et al.* (2012)
Telecommunication industry	Oyedijo (2012)

2.3 Critical Analysis of the Review

Critical analysis has been carried out in many dimensions such as agile manufacturing enablers and methodologies for analysis; agile manufacturing impediments and methodologies for analysis; agile manufacturing performance outcomes and analysis; and agile manufacturing tools, techniques and methodologies used.

2.3.1 Agile Manufacturing Enablers and Methodologies for Analysis

Agile Manufacturing Enablers (AMEs) are the factors those have the capability to provide or enable or enhance the level of agility in the AM system. Few recent works on AME are detailed here. Haq and Boddu (2015) proposed an Analytical Hierarchy Process (AHP)-based framework to prioritise enablers for agile supply chain using AHP, in the context of Indian food processing industries for developing strategies in order to improve supply chain agility. Routroy *et al.* (2015) proposed a methodology by combining the fuzzy synthetic extent of AMEs weight and the average fuzzy performance ratings for calculating the Fuzzy AM Index of the AMEs for measuring the agility of the enterprise. Vinodh and Aravindraj (2013) identified enablers and used multi grade fuzzy and fuzzy logic approaches for the agility assessment and the results were benchmarked. Gunasekaran (1998) reviewed the concepts of AM and its enablers, through developing a framework for enhancing the competitiveness of manufacturing industries. Vázquez-Bustelo *et al.* (2007) adopted a systematic approach for the analysis of AMEs in an integrated way and relating them to environmental characteristics and business performance. Aravind *et al.* (2013) focused on the application of graph theory for conceptual modelling the agile system and to compute the dependencies among the agile enablers, criteria and attributes as a top-down approach. From the literature, it is evident that many researchers have carried out research on AMEs and identified AMEs which may be specific or generic in nature. The objectives of these researches along AMEs are different and different methodologies have applied to achieve the objective. However, there is little or no effort made to present a comprehensive analysis of AM concepts, both from a strategic perspective and enabler's points of view in order to motivate the researchers and practitioners in AM research and applications (Gunasekaran, 1998). Sharp *et al.* (1999) have also mentioned that there is a need for a model that details all the key AMEs those are required for a company to become an AM organisation.

2.3.2 Agile Manufacturing Impediments and Methodologies for Analysis

The Agile Manufacturing Impediments (AMIs) are those which impede the successful implementation of AM. Adoption and instillation of agility and AM principles in manufacturing organisations requires a systematic study of the various paths that may be taken along with a removal of impediments that would exist within this path, allowing efficient and effective introduction of these practices (Hasan *et al.*, 2007). Investigation of these AMIs is necessary to understand and subjugate them. The impediments of AM and their impact cannot be generalized as it depends upon many factors which may be internal or external in general. Although, it is specific but the variations may not be significant as long as nature of organization and business environment remains same. But it is always better to study and analyze the impediments in specific manufacturing environment. For example, Kamarulzaman *et al.* (2015) conducted a survey on the Malaysian palm oil industry to identify the impediments for implementing the agility and found that the highest impediments to implement the agility principles are strict budget, laid back attitude of the employee, lack of understanding between internal and external activities and slow decision-making process. The major problems for any change for the betterment of the company are due to an negative employee attitude as well as improper knowledge about the work activities. Singh *et al.* (2013) Surveyed 102 manufacturing organisations to assess the impediments to achieve strategic flexibility and establish the relationships among various impediments using Analytical Hierarchy Process (AHP). Hasan *et al.* (2007) explored various impediments to adopt AM and established a relationship among the dimensions of impediments through the Interpretive Structural Modelling (ISM) methodology. From our extensive literature review, it is observed that few researches have been carried on AMIs related to its identification and contextual relationship (Kamarulzaman *et al.*, 2015; Singh *et al.*, 2013; Hasan *et al.*, 2007). Therefore, there is a need to identify, classify, investigate and analyze the impediments of AM in order to develop strategies to mitigate/overcome/minimize their adverse impact on AM.

2.3.3 Agile Manufacturing Performance Outcomes and Analysis

Performance is concerned with what happened in the past or what is happening in the present instance and therefore, it is observable and measurable. Performance measurement is indispensable to manufacturing enterprise. The manufacturing industries have been putting resources and efforts to adopt and implement AM with objectives of achieving better performances along many dimensions. The assessment of AM along the performance outcomes along different timeline gives the clear status of improvement. Therefore, the identification and analysis of AM performance outcomes is essential. The AM performance outcomes are both qualitative as well as quantitative in nature. Therefore many researchers have adopted different methodologies to assess the performance outcomes of AM. AM has positive impact on financial performance (Yusuf and Adeleye, 2002, Vázquez-Bustelo *et al.*, 2007 and Inman *et al.*, 2011). AM improves both operational and financial performance (by developing manufacturing strength) whereas the greatest impact is noted in market performance (Vázquez-Bustelo *et al.*, 2007). Inman *et al.* (2011) concluded that AM has a direct positive relationship with the operational performance of the firm. The operational performance of the firm has a direct positive relationship with the marketing performance of the firm whereas the positive relationship exists between the operational performance and the financial performance which is mediated by the marketing performance. The literature suggests that various researchers had studied various aspects of AM performance and applied different analytical tools to analyze it. Zerenler (2007) explored the relationship between the agility and business performance and the effect of the alignment between AM and IT on business performance in the textile industry.

2.3.4 AM Tools, Techniques and Methodologies Used

Since the beginning of the 21st century, many industries are trying to implement AM and measure their performance after implementation. Figure 2.5 gives a detailed idea about the number of times various tools and techniques used by different researchers. Table 2.5 presents a review of the literary contributions to identify the tools, techniques, and methodologies used in AM. MCDM methods like Analytical. Hierarchy Process (AHP) (Erande and Verma, 2008; Meade and Sarkis, 1999; and Routroy *et al.*, 2015), Analytical Network Process (ANP) (Agarwal. *et al.*, 2006; Sarkis *et al.*, 2007; and Hasan *et al.*, 2012), TOPSIS (Mishra *et al.*, 2013; and Sahu *et al.*, 2016a), Interpretive Structural Modelling (ISM) (Hasan *et al.*, 2009a; Chang *et al.*, 2013; and Sindhwani and Malhotra, 2016b) are used by various researchers on different topics like manufacturing agility improvement, for exploring relationships among various criteria, to develop agility measurement tool, supplier selection etc. Fuzzy evaluation method has been taken into consideration by different researchers (Mishra *et al.*, 2015; and Sahu *et al.*, 2016b) for comparison of performance, development of agility index and assessment of manufacturing agility. Multi Agent System is an intelligent system, which has the capabilities to meet the characteristics such as modifiable, extensible, reconfigurable, adaptable and fault tolerant and this gives an effective way to calculate the agile scheduling. AI has largely enabled autonomy functions (handled by software agents) in enterprise agility.

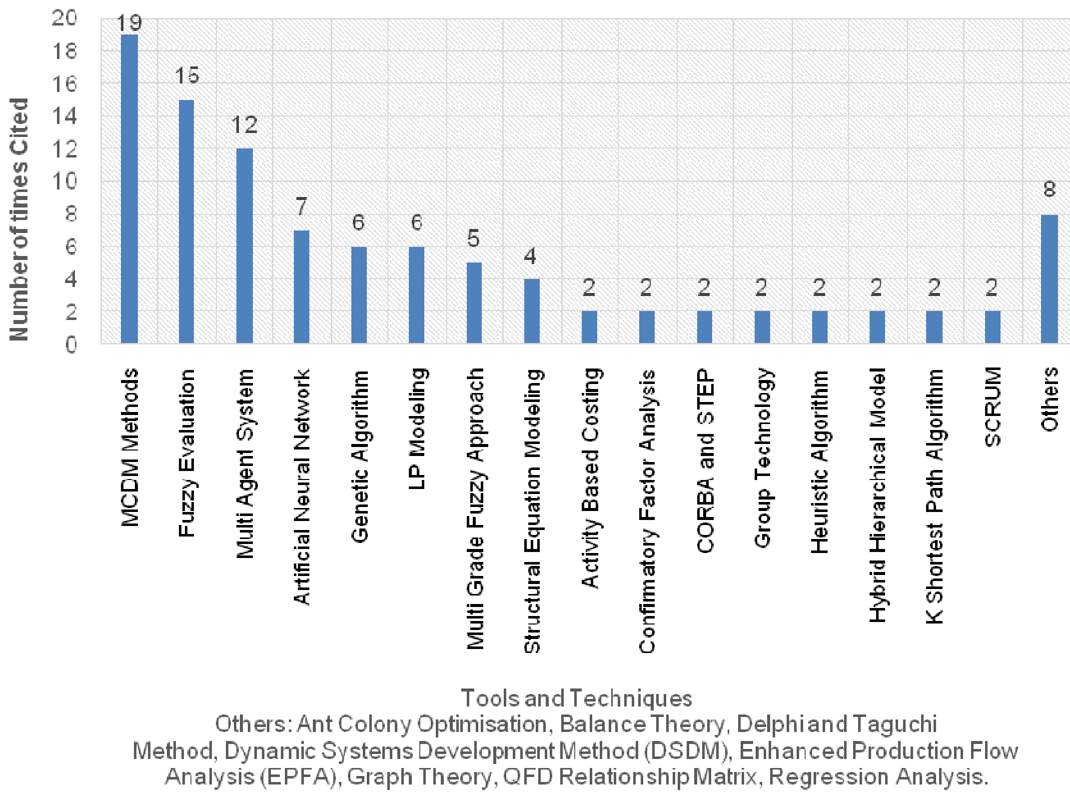

Figure 2.5: Number of research papers published using each tools/ techniques/ methodologies

Computer systems are applying techniques of artificial intelligence e.g. fuzzy rules, knowledge based logic, neural networks, etc. to improve the quality of activities (Huang and Nof, 1999). Genetic Algorithm helps to generate improved production schedules reactively against the disturbances in AM systems like delays of manufacturing operations and addition of new jobs (Tanimizu *et al.* 2006). Linear programming model is being used for modelling the resource selection involving multi-products, multi machines and multi-routes in AM enterprises. For agile software development and project management SCRUM is often used by the researchers. Structural equation modelling helps to quantify the impact of agile operation on operational performance of the industry (Hallgren and Olhager, 2009; and Inman *et al.*, 2011).

Table 2.6: Distribution of references by AM tools/ techniques/ methodologies

Tools and techniques used for analysis of AM	**References**
Multi Criteria Decision Making (MCDM)	Erande and Verma (2008); Meade and Sarkis (1999); Pandey and Garg (2009); Agarwal. *et al.* (2006); Routroy *et al.* (2015); Sarkis *et al.* (2007); Hasan *et al.* (2012); Hasan *et al.* (2008); Hasan *et al.* (2009b); Hasan *et al.* (2009c); Meade and Rogers (1997); Vinodh *et al.* (2010a); Mishra *et al.* (2013); Hasan *et al.* (2009a); Hasan *et al.* (2007); Chang *et al.* (2013); Sindhwani and Malhotra (2016b) ; Vinodh et al. (2013); Drake *et al.* (2013)
Fuzzy Evaluation	Wang (2009); Jassbi *et al.* (2010); Sindhwani and Malhotra, (2016a); Zandi and Tavana (2011); Lin *et al.* (2006a,b); Chandna (2008); Tsourveloudis and Val.avanis (2002); Bottani (2009); Vinodh and Aravindraj (2013); Subbu *et al.* (1998); Vinodh and Devadasan (2011); Garbie *et al.* (2008); Su *et al.* (2008); Vinodh and Chintha (2011); Shih and Lin (2002)
Multi Agent System	Puik and van (2010); Van *et al.* (2012); Van *et al.* (2010); Telgen *et al.* (2013b); Madureira *et al.* (2011); Wang and Lin (2009); Wang *et al.* (2003); Frei and Whitacre (2012); Monostori *et al.* (2006); Rabelo (2003)
Artificial Neural Network	Huang and Nof (1999); Cheng *et al.* (1998); Rajan (1996); Chan and Zhang (2002); Monplaisir (2002); Luo *et al.* (2009); Gmytrasiewicz *et al.* (1995)
Genetic Algorithm	Su *et al.* (2003); Cao and Gao (2006); Tanimizu *et al.* (2006); Gaafar and Masoud (2005); Hsu (2007); Khoo and Loi (2002)
Multi Grade Fuzzy Approach	Sekar *et al.* (2015); Vinodh *et al.* (2010d); Vinodh and Prasanna (2011); Yang an Li (2002); Vinodh *et al.* (2012b)
LP Modeling	Costantino *et al.* (2012); Wu *et al.* (1999); Rao *et al.* (2006); Fung *et al.* (2008); Lalmazloumian *et al.* (2013)
Structural Equation Modeling	Inman *et al.* (2011); Vinodh *et al.* (2012a); Hallgren and Olhager (2009); AL-Tahat and Bataineh (2012)
Activity Based Costing	Vinodh *et al.* (2009c); Fujii *et al.* (2000a);
Confirmatory Factor Analysis	Mashayekhi *et al.* (2011); Dubey and Gunasekaran (2015)
CORBA and STEP	Bhandarkar and Nagi (2000); Zhou and Nagi (2002)
Group Technology	Iyer and Nagi (1995); Iyer and Nagi (1997)
Heuristic Algorithm	He *et al*. (2001); He and Babayan (2002)
Hybrid Hierarchical Model	Yu and Krishnan (2004); Zhou *et al*. (2003)
K Shortest Path Algorithm	Zhang and Sharifi (2007); Pan and Nagi (2010)
SCRUM	Grimheden (2013)
Ant Colony Optimization	Liao and Liao (2008)
Balance Theory	Yauch (2007)
Delphi and Taguchi Method	Devadasan *et al*. (2005)
Dynamic Systems Development Method (DSDM)	Chen *et al.* (2007)

Tools and techniques used for analysis of AM	References
Enhanced Production Flow Analysis (EPFA)	Prince and Kay (2003)
Graph Theory	Aravind *et al*. (2013)
QFD Relationship Matrix	Tseng and Lin (2011)
Regression Analysis	Yusuf *et al*. (2004)

2.4 Conclusions

This study compiles and analyzes that the various reported definitions of AM reflecting goals, principles and scope. It also presents a review of 300 research papers on AM during 1993-2016 with a focus on research contribution, research methodologies, regional importance, author profile, type of industry, and different tools, techniques and methodologies used. Followings are the findings drawn from the current study:

- Research on AM is being conducted all across the globe including developed, emerging and under developed countries. However USA has outnumbered all the countries with approximately one third of the research followed by UK, India and China.
- Academicians from various research institutes have contributed to a major portion of the research on AM than the practitioners. This could be because practitioners are giving more importance on the implementation of AM rather than publication of research papers. Also many academicians are working in co-ordination with industry personnel for the implementation of AM.
- Most of the research papers are found to be either descriptive or empirical in nature. A lot of importance is being given towards the AM performance measurement and process analysis. Researchers have also focused on the real time case studies in different industries to analyze the available data for deciding the future goals.
- The research on AM has picked up from the starting of 21st century. Automotive and electronics product manufacturing industries have been the focus of AM implementation but it also has been adopted by other type of industries. However, the adoption of AM in telecom industry, food industry, casting industry and service industries are not widespread due the fear of high implementation cost and uncertainty of future.
- MCDM tools have been widely used by various researchers on different aspects of AM like manufacturing agility improvement, for exploring relationships among various criteria, to develop agility measurement tool, supplier selection etc. whereas as tools like benchmarking process is hardly used in AM for performance measurement.

- AM improves both the operational and financial performance of the industry by optimising the manufacturing capability which leads to a better market performance.

2.4.1 Limitations and Future Research Issues

Although the current research on AM is promising, it is being mostly conducted only for country specific and industry specific. But hardly any researcher has ever put focus to develop a generic framework for the implementation and performance analysis of AM. The following limitations and future research issues are identified from the current study.

- Some of the quality papers related to AM or agility may have been left out of this review because of the limitations in the search methodology. Mainly AM in manufacturing industry was taken into consideration in the current study. Agile supply chain and agility in software development or new product development are mostly excluded.
- The research on AM through empirical and exploratory studies has led to many frameworks with divergent views. Sometimes, it creates ambiguity among the practitioners to select the appropriate steps. Therefore, there is a strong and urgent need to analyze these divergent views for developing generic AM implementation framework.
- The AM performance outcomes are both qualitative as well as quantitative in nature. The manufacturing industries have been putting significant resources and efforts to adopt and implement AM for better performance along different dimensions. Therefore, the identification and analysis of AM performance outcomes should be carried out.
- There is little or no effort made to present a comprehensive analysis of AM concepts, both from a strategic perspective and enablers and impediments points of view to motivate the researchers and practitioners in AM research. There is a need to identify, classify, investigate and analyze the enablers and impediments of AM in order to develop strategies to mitigate their adverse impacts.
- Various researchers in AM have used many tools/ techniques/ methodologies in their research. Future research is required to develop the standard tools/techniques /methodologies for AM. The study should also explore the combination of these tools and techniques for more precise result.

CHAPTER 3

Agile Manufacturing Enablers

3.1 Introduction

Agile Manufacturing (AM) has gained tremendous recognition and acceptability among the manufacturing engineers since the last decade. AM has evolved as a revolutionary way of manufacturing and assembling the products based on rapidly changing market and customer demands (Hormozi, 2001). External changes in both market and customer preference has an impact on the competitiveness of any organization. AM was defined as a production model that has resulted from changes in external environment (Goldman *et al.*, 1995; Vokurka and Fliedner, 1998; Sharifi and Zhang, 1999; Zhang and Sharifi, 2000; Ismail *et al.*, 2006; and Yusuf and Adeleye, 2002). Only those organizations which are sensitive to changes and are able to dynamically modify their processes and products to satisfy the demands can sustain in the business and be capable of making profits. The emphases on quick response to change, ability to thrive in unanticipated changing scenarios, leveraging the changes to gain strategic advantage have been widely advocated (Gunasekaran, 1998; Zhang and Sharifi, 2000; Sarkis, 2001; Hooper *et al.*, 2001; Brown and Bessant, 2003; and Gunasekaran *et al.*, 2008). Various authors have concurred that the tools for achieving AM are value engineering, concurrent engineering, business information systems, control systems, information technology, supply chain, knowledge management, management support, flexible work force, rapid prototype tools, electronic commerce and electronic data interchange (Gunasekaran, 1999 and Vinod and Kuttalingam, 2011). Agile Manufacturing Enabler (AME) is the factor that has the capability to provide or enable or enhance the level of agility in the agile manufacturing system. Many researchers have carried out research on AMEs and identified AMEs which may be more or less generic in nature.

AM includes both management and technological enablers. The focus on management based AM enablers are given more importance by the researchers in comparison to technology based AM enablers (Vinodh and Kuttalingam, 2011). Although alignment among competitive drivers, agility capabilities and providers are all very critical in making an enterprise agile, it is difficult for an enterprise to achieve agility due to lack of an efficient approach for agile development planning (Tseng and Lin, 2011). There exists a need to comprehensively model the agile system with key enablers as well as to find the interdependency that exists between the agile enablers in an unpredictable environment (Aravind *et al.*, 2013). Therefore, it is essential that the right AMEs should be selected to enhance the agility level of manufacturing system in general and of AM in specific. Their current status should be assessed and gap should be identified so that efforts would be streamlined to reach the desired level of performance along these selected AMEs. This selection of AMEs is manufacturing environment specific as priority of competitive strategies, internal and external business environment, and nature of the product are the basic and relevant input for the analysis. It is complicated in nature as all the interactions in terms of their driving and dependence power have to be captured considering the manufacturing environment. The proposed methodology using ISM-FMICMAC analysis is the systematic analysis of AMEs to select the right AMEs, where the company must focus and put effort and, by taking inputs from multiple experts' consideration a strategy is developed to deal with this complex nature of the problem. The benchmarking approach should be developed for identified AMEs for successful implementation of AM and thus enhance its agility. This is an approach that has not been attempted before. A case study has been carried out to explain the salient features of the proposed methodology.

This paper is organized as follows: the literature review on agile manufacturing enablers is in Section 3.2. The proposed methodology for successful implementation of AM is presented in Section 3.3. The ISM and Fuzzy MICMAC analysis for analyzing AMEs are discussed in Section 3.3.1 and Section 3.3.2 respectively. The application of proposed methodology in an Indian manufacturing company is presented in Section 3.3.3. The Conclusions of the case company are discussed in Section 3.4 and Section 3.4.1 presents Limitations and Future Research Directions.

3.2 Agile Manufacturing Enablers

The manufacturing organization focusing on AM should identify the agile manufacturing enablers (AMEs) and then define the domain of each enabler so that right AMEs can be selected in a specific manufacturing environment. Many researchers have carried out various studies related to AMEs, agile enablers and agility which may be specific or generic in nature. They have also carried out various analysis using different tools and techniques. Avazpour *et al.* (2014) developed a framework based on the fuzzy multiple criteria decision making approach to identify the most appropriate agility enablers to be implemented by a subsidiary company of the National Iranian Gas Company and concluded that team building is the best agility enabler. Tseng and Lin (2011) developed a QFD-based framework to logically link up and deal with issues of the interface and coordination among the agility providers, capability and driver. In addition, a fuzzy agility index (FAI) composed of agility capability ratings and its relation-weights with drivers was developed for the measurement of agility in an enterprise. Aravind *et al.* (2013) applied graph theory for conceptual modelling the agile system and to compute the dependencies among the individual agile enabler, criteria and attributes as a top-down approach. Raj *et al.* (2014) analyzed the gaps in an agile manufacturing implementation project using hybrid Analytic Network Process (ANP)-Technique for Order Performance by Similarity to Ideal Solution (TOPSIS). Nejad *et al.* (2014) investigated the relationship between entrepreneurial orientation and agility in manufacturing firms taking statistical sample consisting of 100 manufacturing firms of Kerman Province and confirmed a positive and significant relationship between them. Pullan (2014) proposed concurrent engineering (CE) framework using effective application of information technology and knowledge-based engineering for adoption and implementation of agile manufacturing practices.

Aravindraj and Vinodh (2014) developed a 40-criteria agility assessment model and was applied to an Indian electrical relays manufacturing organization. The current agility level of the case organization was determined and was used for the gap analysis and agility improvement proposals. Mishra *et al.* (2014) developed a fuzzy based integrated agility appraisement module, incorporated the variations in the Decision Makers' (DMs) risk bearing attitudes and analyzed the effects of variations in DMs' attitudes toward agility estimation. Gurd and Ifandoudas (2014) used an action research approach in a single organization to investigate the practicality and usefulness of an agility-focused balanced scorecard (BSC) system. Vinodh and Sakthivel (2015) carried out agility assessment for a case organization using Multi Grade Fuzzy and Fuzzy logic approaches. The results were benchmarked to identify the agility gaps and improvement proposals. Vinodh and Aravindraj (2015) identified AMEs and used multi grade fuzzy and fuzzy logic approaches for the agility assessment and the results were benchmarked.

Based on the literature survey in AM and discussion held with experts in Indian manufacturing environment, various enablers have been identified that promote AM and have been grouped (i.e. Adaptability (ADP); Product and Process Automation (PPA); Supply Chain Integration (SCI); Core Competency (CCT); Supply Chain Key Partner's Alacrity (SCP); Devolution of Authority (DOA); Information Visibility and Transparency (IVT); Manufacturing Management (MFM); Customer Relationship Management (CRM); Supplier Relationship Management (SRM); Human Resource Management (HRM)) (see Table 3.1). Each group is called as Agile Manufacturing Enabler (AME). The detail description of the enablers is also discussed in Table 3.1.

Table 3.1: Agile manufacturing enablers for agile manufacturing

AME	**Description**	**Reference**
Adaptability (ADP)	It is the capability of a system to respond to both predictable and unpredictable changes. The changes are not restricted to technology (i.e. new and better technologies), business environment, customer requirements, socio-economic, products and services, risk etc.	Kidd, 1995; Yusuf *et al.*, 1996; Sharifi and Zhang 1999; Zhang and Sharifi, 2000; Hormozi, 2001; Ramasesh *et al.*, 2001; Zhang *et al.*, 2002; Jackson and Johansson 2002; Wang and Lo, 2003; Lim and Zhang, 2004; Vazquez-Bustelo *et al.*, 2007; Sherehiy *et al.*, 2007; Erande and Verma, 2008; Vinodh and Devadasan, 2011; Flumerfelt *et al.*, 2012; Dubey and Gunasekaran, 2014 and discussion held with experts.
Product and Process Automation (PPA)	It is the capability of a system to design, produce parts and develop processes with the aim to reduce the lead-times. Use of automated and computer-aided-technologies like Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Process Planning CAPP, automated material handling, packaging etc., lead to reduced design-to-manufacture time.	Kidd, 1995; Ramasesh *et al.* 2001; Jackson and Johansson 2002; Lim and Zhang, 2004; Ramesh and Devadasan, 2007; Sherehiy *et al.*, 2007; Vazquez-Bustelo *et al.*, 2007; Erande and Verma, 2008; Vinodh and Chintha, 2011; Beck, 2012 and discussion held with experts.
Supply Chain Integration (SCI)	It refers to the ability of integrating the operations/activities along the supply chain through respective core-competencies or specializations of various stakeholders. It is achieved through mutual trust, management of inter-relations and intra-relations, integrated procurement, logistics and distribution systems etc.	Kidd, 1995; Lee *et al.*, 1999; Ramasesh *et al.*, 2001; Hormozi, 2001; Vazquez-Bustelo *et al.*, 2007; Samarnayake *et al.*, 2011; Vinodh and Chintha, 2011; Beck, 2012; Flumerfelt *et al.*, 2012 and discussion held with experts.
Core Competency (CCT)	It is the ability of an organization to develop and sustain expertise in a specific domain. Strong R&D, knowledge of latest domain technologies, multi-skilled and enthusiastic work-force, “first time right” design, emphasis on quality	Kidd, 1995; Yusuf *et al.*, 1996; Lee *et al.*, 1999; Sharifi and Zhang 1999; Hormozi, 2001; Ramasesh *et al.*, 2001; Wang and Lo, 2003; Vazquez-Bustelo *et al.*, 2007; Sherehiy *et al.*, 2007; Ramesh and Devadasan, 2007; Erande and Verma, 2008; Vinodh and Devadasan, 2011; Flumerfelt

AME	Description	Reference
	maintenance etc., are antecedents for developing core competency in AM.	*et al.*, 2012; Dubey and Gunasekaran, 2014; Sherehiy and Karwowski, 2014 and discussion held with experts.
Supply Chain Key Partner's Alacrity (SCP)	It refers to the willingness of supply chain partners for active participation, ability to share and take risks, venture into new markets and collaborate with other strategic partners, earn goodwill and reputation etc.	Yusuf *et al.*, 1996; Sharifi and Zhang 1999; Ramasesh *et al.*, 2001; Jackson and Johansson 2002; Vazquez-Bustelo *et al.*, 2007; Bergvall-Forsberg and Towers, 2009; Samarnayake *et al.*, 2011; Flumerfelt *et al.*, 2012 and discussion held with experts.
Devolution of Authority (DOA)	It refers to the ability to define and delegate decision making powers for reducing delays across various dimensions. Improvised organizational structure, creating cross-functional teams, quality circles, auditors and consultants etc. are some of the ways of decentralizing the decision making process.	Kidd, 1995; Yusuf *et al.*, 1996; Vazquez-Bustelo *et al.*, 2007; Ramesh and Devadasan, 2007; Dubey and Gunasekaran, 2014 and discussion held with experts.
Information Visibility and Transparency (IVT)	It refers to the ability to capture and share accurate and real-time information along various stake holders in the right form/details. This will provide intelligent business platform to analyze, forecast and prepare plans for AM.	Lee *et al.*, 1999; Hormozi, 2001; Coronado 2003; Vazquez-Bustelo *et al.*, 2007; Ramesh and Devadasan, 2007; Vinodh and Chintha, 2011; Beck, 2012; Dubey and Gunasekaran, 2014 and discussion held with experts.
Manufacturing Management (MFM)	It refers to the management of manufacturing activities through a robust manufacturing planning and control, production methodologies. It also includes efficient waste management, concurrent engineering for "first time right" design/manufacturing plan and managing the product life cycle.	Kidd, 1995; Yusuf *et al.*, 1996; Ramasesh *et al.*, 2001; Lim and Zhang, 2004; Leita and Restivo, 2006; Vazquez-Bustelo *et al.*, 2007; Ramesh and Devadasan, 2007; Vinodh *et al.*, 2009; Vinodh and Devadasan, 2011; Vinodh and Chintha, 2011; Beck, 2012; Dubey and Gunasekaran, 2014; Pullan, 2014 and discussion held with experts.
Customer Relationship Management (CRM)	It is the ability to maintain a positive and sustainable relationship with the customer by satisfying their ever increasing requirements by maintaining appropriate level of responsiveness. There should be a strong integration between customer relationship management and AM.	Sharifi and Zhang 1999; Zhang and Sharifi, 2000; Jackson and Johansson 2002; Wang and Lo, 2003; Ramesh and Devadasan, 2007; Sherehiy *et al.*, 2007; Erande and Verma, 2008; Dubey and Gunasekaran, 2014 and discussion held with experts.
Supplier Relationship Management (SRM)	It refers to the management the supplier base. The processes like supplier development, supplier switching, supplier selection, supplier certification, supplier evaluation etc. come under this. There should be a natural fit supplier relationship management and AM.	Vazquez-Bustelo *et al.*, 2007; Dubey and Gunasekaran, 2014 and discussion held with experts.
Human Resource Management (HRM)	It relates to the management of human resource through training, development, compensation, recognition, rewards etc. for motivating them and promoting organizational learning.	Kidd, 1995; Yusuf *et al.*, 1996; Lee *et al.*, 1999; Wang and Lo, 2003; Vazquez-Bustelo *et al.*, 2007; Ramesh and Devadasan, 2007; Erande and Verma, 2008; Vinodh and Chintha, 2011; Flumerfelt *et al.*, 2012; Dubey and Gunasekaran, 2014 and discussion held with experts.

From the above discussion, it is evident that agility enhancement is the need of the hour. To achieve this, a manufacturing company should assess the current status of agility performance, determine the agility performance gap, select the right AMEs and streamline efforts along those AMEs. A generic set of AMEs had been identified and domain of each AME is specified. The description had been made for each AMEs and literature review is of it is mentioned in Table 3.1. It is very difficult for a manufacturing organization to focus and put efforts to all enablers. The AMEs should be classified considering the interactions (in terms of driving and dependence power) between AMEs to choose the right set of AMEs for enhancing the organizational agility. The interactions between AMEs are qualitative in nature and it should be captured taking judgments from team of multiple experts. Therefore in this study, a methodology proposed using ISM and FMICMAC analysis taking judgments from team of multiple experts to classify and select the right set of AMEs for enhancing organizational agility.

3.3 Proposed Methodology For Successful Implementation of AM

The aim of the proposed methodology (see Figure 3.1) is to identify the right AMEs where the manufacturing companies are focusing to implement AM successfully and enhance its agility. The methodology starts with identifying and defining generic set of AMEs. The domain of each AME should be clearly defined and specified to avoid redundancy and which will be later form the basis for identifying the Key Performance Indicators (KPIs) for each AME. Then the generic set of AMEs should be screened on the basis of their importance in a specific situation in order to select AMEs for that environment. The importance of each AME should be captured on basis of the multiple experts' judgment. For analyzing and establishing the relationship between AMEs in the specific environment, the ISM integrated with FMICMAC algorithm is proposed which is programmed in MATLAB 7.10.0 (R2010a). The step by step procedure of ISM and FMICMAC algorithm is presented in the Section 3.3.1. Inputs from the experts are taken at two stages (i.e. in first stage on binary scale and in second stage on fuzzy scale). In the first stage, the Contextual Relationship Matrix (CRM) among the right AMEs under each category has to be developed on the basis of team of multiple experts' judgments (see Section 3.3.1). The CRMs under each category has to be fed into the ISM algorithm.

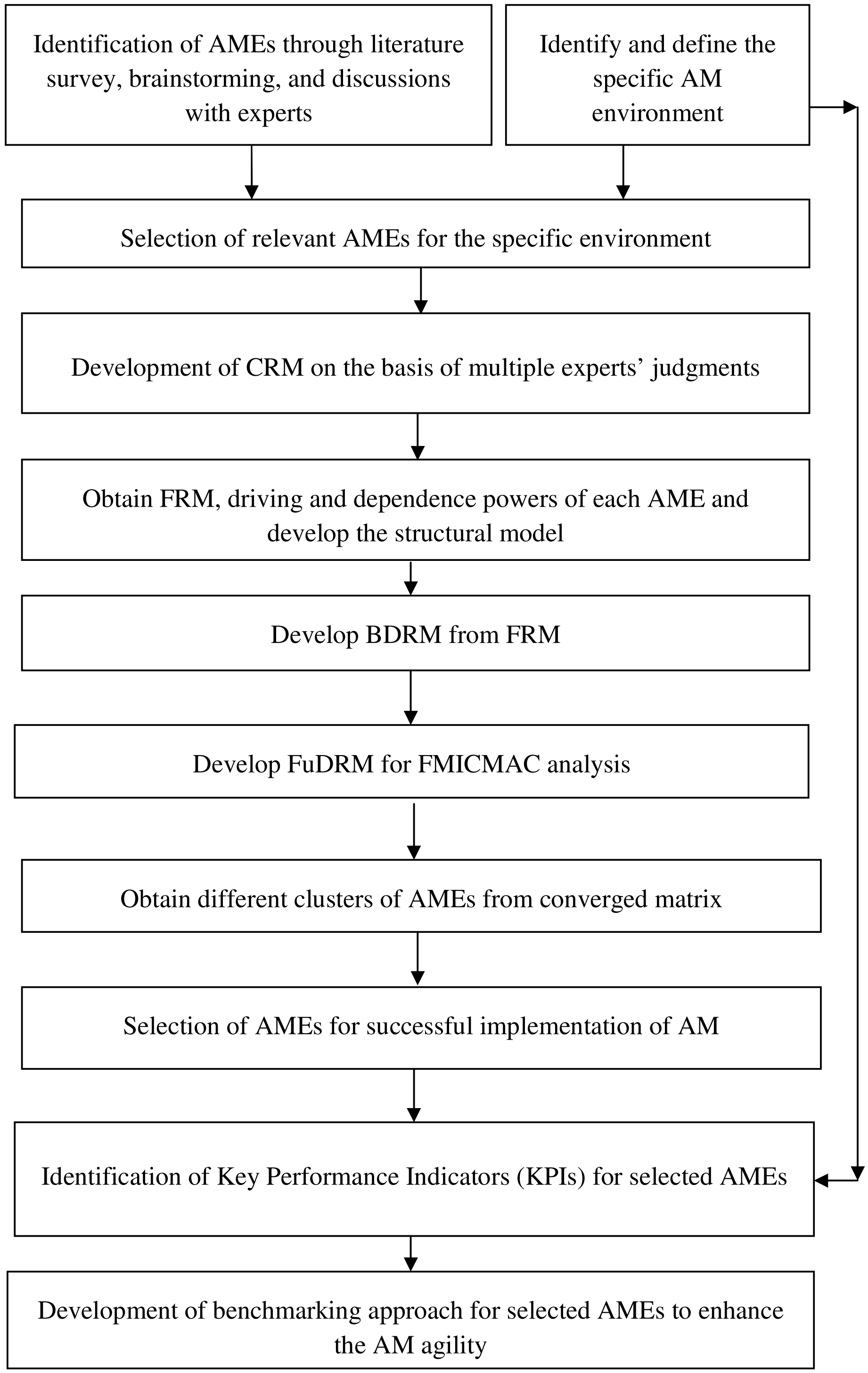

Figure 3.1: Proposed methodology for successful implementation of AM

The CRMs subsequently should be transformed as per the steps in the ISM algorithm (see Section 3.3.1). The fruitful insights in terms of driving and dependence powers of each AME, relationship between them, level partitioning, structural/ ISM model and classification of AMEs will be drawn from the ISM algorithm. The results obtained from the ISM algorithm will certainly help in understandings their relationships. However it is proposed to integrate ISM with FMICMAC analysis, which will provide the experts enough scope in expressing their views that will result in better analysis of relationship between the AMEs. The same team of experts should be consulted (whose inputs have been taken earlier) to develop FuDRM from BDRM. This is the second stage of inputs taken from the experts for FMICMAC analysis and detail algorithm is as mentioned in Section 3.3.2. It will classify the AMEs into four clusters on the basis of driving and dependence power. The AMEs in driver cluster should be selected first for enhancing the agility of AM. The Key Performance Indicators (KPIs) should be identified and the benchmarking approach should be adopted to enhance the performance of these AMEs which in turn will enhance the AM agility.

Although number of enablers have impact directly or indirectly or both ways on the agility performance of a manufacturing system, it is not possible for an organization to focus on all the enablers at a time in order to enhance agility performance level. Therefore, it is essential to identify the AM enablers which have high driving and low dependence power on the agility performance so that manufacturing companies can streamline their efforts accordingly. As the proposed methodology has got the ability to capture the multiple experts' judgments for identifying the right enablers on the basis of driving and dependence power, the obtained results will be more reliable. However, the proposed methodology cannot quantify the impact level of each AME and their combinations on the agility performance. Moreover, it does not provide information regarding the future course of actions for a manufacturing organization, once the selected AMEs is improved to a desired level.

3.3.1 ISM for Analyzing AMEs

ISM methodology has the ability to analyze the AMEs and to show the direction of relationships in manufacturing environment (Sage, 1977). ISM presents a hierarchical structure that depicts the direct and indirect linkages between the various components in a system based on primacy, precedence, and causality over and among each other (Mishra *et al*., 2012). Recently many researchers have used ISM in different areas but not limited to antecedents of Truck Freight Model (TFM) (Dubey *et al*., 2015a), drivers of end-of-life tire management (Kannan *et al*., 2014), factors affecting quality of management education in India (Mahajan *et al*., 2014), barriers in total productive maintenance implementation (Singh *et al*., 2014), factors affecting the reconfigurable manufacturing system (Malhotra, 2014), critical waste factors in office building retrofit projects (Li and Yang, 2014), enablers of organizational commitment (Faisal and Al-Esmael, 2014), study of AM drivers (Mishra *et al*., 2012), analysis of critical success factors (CSFs) of supplier development (Routroy and Pradhan, 2014), green supply chain management (Kannan *et al*., 2014); agility enhancing management practices for agile manufacturing (Hasan *et al.,* 2013) and analysis of the CSFs for successful implementation of ubiquitous manufacturing (Dubey *et al.,* 2015b). In the current study the relationships between the AMEs have to be studied in terms of driving and dependence powers for successful adoption of AM. Therefore, ISM methodology is adopted to know these relationships among the AMEs and develop a structural framework of AMEs. The ISM methodology used in the study is discussed below:

Step 1 The irredundant, properly accounted, relevant and significant AMEs are considered to develop Structural Self-Interaction Matrix (SSIM) based on contextual relationships among the AMEs. These contextual relationships show the way they are related to each other in the manufacturing environment where the study is carried out. They are created considering the experts' judgment. Four symbols (V: AME 'i' leads to AME 'j'; A: AME 'j' leads to AME 'i'; X: AME 'i' leads to AME 'j' and AME 'j' leads to AME 'i' and O: No relationship between AME 'i' and AME 'j') are used for the type of the relation that exists between the AMEs ('i' and 'j').

Step 2 The Initial Reachability Matrix (IRM) is developed by converting SSIM into a binary matrix, substituting V, A, X and O by 1 and 0.

Step 3 The Final Reachability Matrix (FRM) is developed from IRM considering transitivity in the contextual relations of AMEs. Transitivity in the relationship is determined as follows: if AME "i" is related to AME 'j' and AME 'j' is related to AME 'k', then AME 'i' is related to AME 'k'. Then the (i, k) entry in the FRM becomes 1*.

Step 4 Driving and dependence power of each AME is determined by taking summation of the elements along the rows and columns of FRM respectively. The AMEs are ranked on the basis of driving and dependence powers.

Step 5 The level partitions are developed by segregating FRM into different levels. It starts with developing the reachability and antecedent sets for each AME from the FRM. The reachability set of a AME contains factor itself and other factors to which it may reach whereas antecedent set contains AME itself and other AMEs, which may reach to it. The AMEs for which the reachability and intersection sets are same, occupy the top-level in the ISM hierarchy. The top-level AMEs are separated out from the initial set of AMEs and then the process is repeated until all the AMEs are assigned to a level.

Step 6 From the obtained level partitions a lower triangular matrix or canonical matrix is developed. It is just another form of FRM in which AMEs are positioned and clustered according to their level. This canonical matrix forms the basis for developing a directed graph called as digraph. If there is a relationship between AME 'i' and AME 'j', this is shown by an arrow which points from AME 'i' to AME 'j'.

Step 7 The structural model of AMEs is generated by eliminating the transitivity links in the diagraph (obtained in the Step6) and considering the level partitions (in Step 5) and FRM (in Step 4).

Step 8 The structural model of AMEs developed in Step 7 is reviewed for conceptual accuracy. If it is not conceptually accurate, then go to Step1.

Step 9 Based on the driving and dependence powers obtained in the Step 4, Fuzzy MICMAC analysis is carried out (see Section 3.3.2).

3.3.2 Fuzzy MICMAC Analysis for Analyzing AMEs

The use MICMAC analysis has been reported in the literature and some of the recent applications are analysis of lean criteria in machine tool sector (Sharma *et al.*, 2015), analysis of the CSFs for successful implementation of ubiquitous manufacturing (Dubey *et al.*, 2015b), study of the performance measures of world class manufacturing (Digalwar *et al.*, 2015); find out dependency and driving power TQM enablers along with IT resources (Khanam *et al.*, 2015); and analysis of the competitiveness of uncertainty and risk measures in supply chain (Chand *et al.*, 2015). Although MICMAC analysis can classify various factors (i.e. enablers, barriers and criteria) of a problem, there is a limitation in the process. Since the relationships between AMEs are recorded in terms of binary values (either 0 or 1), there is no enough degree of freedom for experts in expressing the strength of relationship between the factors which could be either very weak, weak, medium, strong or very strong(Dubey *et al.*, 2015b) . One can find the use of Fuzzy MICMAC analysis in recent literatures (i.e. systematic analysis of impediments of supplier development (Kumar and Routroy, 2014), study the customer receptivity aspects of a telecom service provider organization (Pramod and Banwet, 2014); understand possible linkage between variables that constitute a lean manufacturing enterprise (Dubey and Singh, 2015); analysis of supply chain management barriers (Gorane and Kant, 2015); and calculation of the Risk Priority Number (RPN) (Venkatesh *et al.*, 2015) which are used in different areas to get more accurate and better analysis. The objective of the FMICMAC analysis is to divide the AMEs into four quadrants namely autonomous, dependent, linkage and driver. The division of quadrants is made on the basis of driving and dependence power of AMEs. Driving powers of an AME shows the influence level to other AMEs whereas the dependence powers of an AME represents the degree of influence by other AMEs. The significance of the four quadrants is discussed below:

Driver quadrant: The AMEs with high driving and low dependence powers are clustered in this quadrant. Thus, the AMEs grouped in this quadrant has high capability of influencing other AMEs in making the manufacturing system more agile. The manufacturing company should put efforts and resources on these enablers to improve their performance to a desired level which will in turn enhance the agility.

Autonomous quadrant: The AMEs with low driving and dependence powers are clustered in this quadrant. They do not have any cause or effect on any other AMEs and are not much related to enhance the agility. Thus, the AMEs falling in this quadrant can be safely ignored.

Dependent quadrant: The AMEs with low driving and high dependence powers are clustered in this quadrant. These AMEs can get influenced and improved by other AMEs.

Linkage quadrant: Generally, the AMEs having medium driving and dependence power are fallen in this quadrant. They have feedback effect on themselves. However, these AMEs cannot be neglected but they are to be maintained and monitored constantly in order to achieve the agility.

Table 3.2: Possible relationship strength between AMEs

Dominance of Interaction	No	Very Low	Low	Mediu m	High	Very High	Full
Grade	N	NL	L	M	H	VH	F
Value on the Scale	0	0.1	0.3	0.5	0.7	0.9	1

The steps mentioned below are to be followed to obtain above mentioned four quadrants (Pfohl *et al.*, 2011 and Qureshi *et al.*, 2008):

Step 1 Replace all the diagonal elements along with the transitive relationships with 0's to obtain a Binary Direct Relationship Matrix (BDRM).In the FRM (see step 4 of the ISM algorithm in the Section 3.1)

Step 2 Using the same experts' judgments (see step 1 of the ISM algorithm in the Section 3.1), the relationships as mentioned in Table 3.2 between the AMEs in the BDRM should be recollected to obtain fuzzy Direct Relationship Matrix (FuDRM).

Step 3 The FuDRM's power is raised by fuzzy matrix multiplication (rule: $C = \max_k \{\min(a_{ik}, b_{kj})\}$ where $A = [a_{ik}]$, $B = [b_{kj}]$) till it is converged. The convergence point can be determined where the driving and dependence powers of AMEs are stabilized or cyclic in their variation with certain periodicity.

Step 4 Based on the new driving and dependence powers obtained from the final converged matrix, driver dependence diagram is to be plotted (with dependence power along the X-axis and driving power along the Y-axis).The maximum values (both in converged matrix and FRM) of driving and dependence power obtained and on the basis of experts' opinion, values of driving and dependence power (i.e. to draw horizontal and vertical line) are fixed to classify the AMEs into four groups (i.e. driver, autonomous, dependent and linkage).

3.3.3 Application of Proposed Methodology in an Indian Manufacturing Company

The proposed methodology was applied to an Indian electrical hardware manufacturing company for analyzing the AMEs. As per company's policy, to protect its confidentiality, to maintain good relationship with the senior executives and to conduct further research, name of the company is not disclosed and it is named as 'X' in this paper. The company is a large scale manufacturer and a prominent supplier for many manufacturing companies in India and abroad. The case company has a turnover more than INR 20 billion and has adopted the agile manufacturing to become more customers centric. Although the company has certain standard products manufactured but its major business is to offer highly customized and innovative products. With respect to its supply chain environment, it has developed an excellent supply base close to its manufacturing plant. In order to attain its own manufacturing excellence, it has been investing significant effort and resources specifically in research and development, and employee skill development. It is well known for its order winning capability and organizational culture. It also produces wide variety of products in comparison to its competitors. Characterized with these features, the company X is able to be aggressive in taking risk along many competitive dimensions to attract and retain its customer base. However, the company X does not have systematic evidence established to improve its agility. Therefore, the proposed approach is an interest to company to get right direction for optimum utilization of its resources and efforts for enhancing agility. It was decided to form a cross functional team which consists of six experts drawn from manufacturing, purchasing, logistics, marketing, finance and human resource development department of the case company. All the six experts have professional degree and have a sound knowledge on agility and business environment as they have more than 7-10 years of experience in the case company. A detailed discussion was held with them. When discussed with the experts regarding the AMEs, there were different aggressive opinions among the experts. The above proposed methodology and its objectives were explained to the experts and were asked to give their opinions at two stages. The company experts were motivated with the proposed methodology and agreed to cooperate but repeatedly cautioned not to reveal the identity of the company. The eleven AMEs as mentioned in previous section were discussed with the team of experts to check for accountancy, relevancy, and significance. Finally, it was concluded that the eleven AMEs were significant for the company's AM. The relationships among 11 AMEs were explored with the help of a questionnaire administered to the experts. The questionnaire consists of 55 questions to collect the qualitative opinions about the relationship between the AMEs. For collecting the qualitative opinions, six experts were asked to choose one among the following four types of relationships (i.e. V, A, X and O) between the AMEs (see step 1 in Section 3.3.1). Depending upon the choice made, the contextual relationships are developed among the AMEs in order to develop SSIM and it is mentioned in Table 3.3. The IRM is developed by substituting V, A, X and O by 1 and 0 in Table 3.3.

Table 3.3: SSIM for AMEs of the case company

	ADP	PPA	SCI	CCT	SCP	DOA	IVT	MFM	CRM	SRM	HRM
ADP	1	V	V	V	V	V	V	V	V	V	V
PPA		1	V	X	V	O	V	X	V	O	O
SCI			1	V	X	A	A	V	V	V	V
CCT				1	A	O	O	A	A	A	A
SCP					1	A	A	V	O	X	V
DOA						1	V	V	V	V	V
IVT							1	X	V	X	V
MFM								1	V	V	X
CRM									1	A	A
SRM										1	X
HRM											1

ADP: Adaptability; PPA: Product and Process Automation; SCI: Supply Chain Integration; CCT: Core Competency; SCP: Supply Chain Key Partner's Alacrity; DOA: Devolution of Authority; IVT: Information Visibility and Transparency; MFM: Manufacturing Management; CRM: Customer Relationship Management; SRM: Supplier Relationship Management; HRM: Human Resource Management

The transitivity of the contextual relation and IRM are considered to develop FRM. The driving and dependence power of each AME is calculated to develop FRM (see Table 3.4). The ranking of each AME in terms of driving and dependence power is also mentioned in Table 3.4. The level partition of AMEs is performed by developing the reachability and antecedent sets for each AME from the FRM. Five iterations are carried out to assign each AME to a level and by the process, five levels are formed. ISM model of AMEs for the case company was developed and shown in Figure 3.2. FMICMAC analysis was carried out revisiting driving and dependence power of each AME in Table 3.4 and the non-zero cells were replaced by fuzzy numbers depending on the driving and dependence power of the corresponding AMEs on the basis of collective judgments of six experts. By the process, FuDRM was formed and is shown in Table 3.5.

Table 3.4: FRM with driving and dependence powers for AMEs of the case company

	ADP	PPA	SCI	CCT	SCP	DOA	IVT	MFM	CRM	SRM	HRM	DRP	Rank
ADP	1	1*	1*	1*	1*	1*	0	1*	1*	1*	1*	10	II
PPA	0	1	1*	1*	1*	0	0	1*	1*	1*	1*	8	III
SCI	0	1*	1	1*	1*	0	0	1*	1*	1*	1*	8	III
CCT	0	0	0	1	1*	0	0	0	1*	1*	1*	5	V
SCP	0	1*	1*	1*	1	0	0	1*	1*	1*	1*	8	III
DOA	0	0	1*	1*	1*	1	0	1*	1*	1*	1*	8	III
IVT	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	11	I
MFM	0	0	1*	1*	1*	0	0	1	1*	1*	1*	7	IV
CRM	0	0	1*	1*	1*	0	0	1*	1	1*	1*	7	IV
SRM	0	0	1*	1*	1*	0	0	1*	1*	1	1*	7	IV
HRM	0	0	1*	1*	1*	0	0	1*	1*	1*	1	7	IV
DEP	2	5	10	11	11	3	1	10	11	11	11		
Rank	V	III	II	I	I	IV	VI	II	I	I	I		

DEP: Dependence Power; DRP: Driving Power

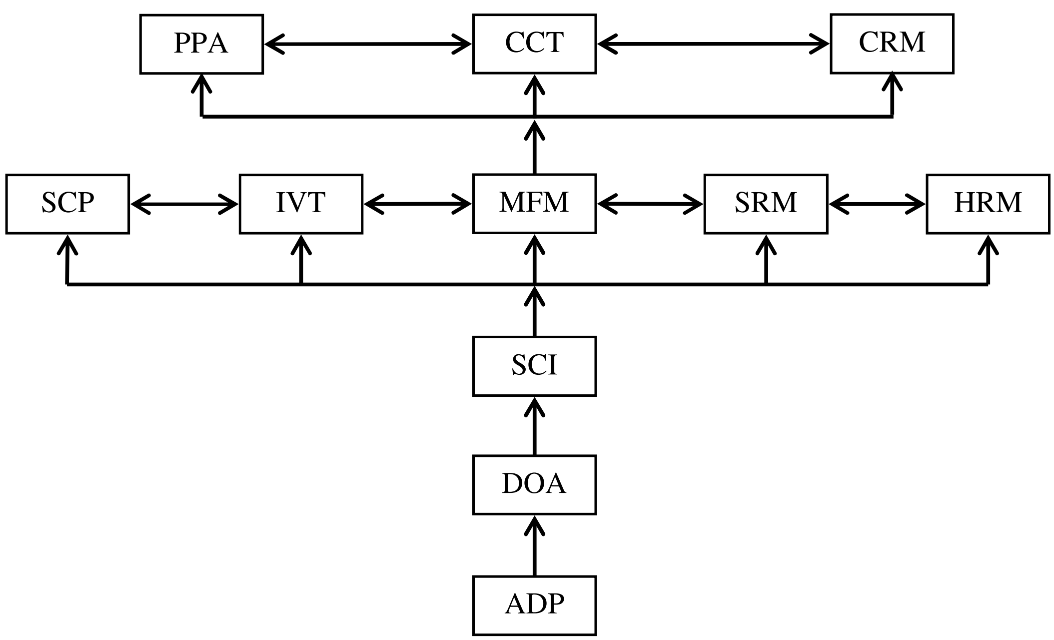

Figure 3.2: ISM model of AMEs

Table 3.5: Fuzzy direct relationship matrix for AMEs of the case company

	ADP	PPA	SCI	CCT	SCP	DOA	IVT	MFM	CRM	SRM	HRM
ADP	0	0.7	0.5	0.5	1	0.9	0	0.7	0.9	0.7	0.5
PPA	0	0	0.7	0.7	0.7	0	0	0.9	1	0.7	0.5
SCI	0	0.5	0	0.5	0.5	0	0	0.9	0.9	1	0.7
CCT	0	0	0	0	0.5	0	0	0	0.5	0.5	0.7
SCP	0	0.7	0.9	0.9	0	0	0	0.7	0.7	0.5	0.5
DOA	0	0	0.9	0.9	0.7	0	0	0.9	0.7	0.7	0.7
IVT	0.9	1	1	0.7	0.7	0.7	0	0.9	0.9	0.9	0.5
MFM	0	0	0.5	1	0.5	0	0	0	0.7	0.7	0.5
CRM	0	0	0.7	0.7	0.7	0	0	0.7	0	0.5	0.7
SRM	0	0	0.9	0.7	0.7	0	0	0.9	0.7	0	0.9
HRM	0	0	0.7	0.9	0.7	0	0	0.9	0.9	0.7	0

The FuDRM's power was raised by fuzzy matrix multiplication to get converged matrix and is mentioned in Table 3.6. Finally FMICMAC Driver Dependence Diagram of AMEs was developed on the basis of (see Table 3.6) and is shown in Figure 3.3.

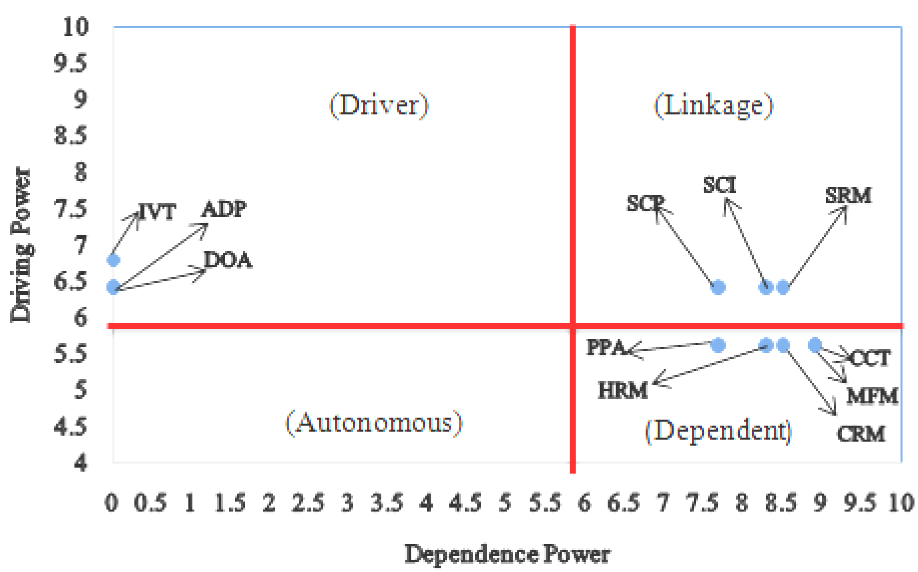

Figure 3.3: FMICMAC driver dependence diagram for AMEs of the case company

Table 3.6: Converged matrix for AMEs of the case company

	ADP	PPA	SCI	CCT	SCP	DOA	IVT	MFM	CRM	SRM	HRM	DRP
ADP	0	0.7	0.7	0.9	0.7	0	0	0.9	0.9	0.9	0.7	6.4
PPA	0	0.7	0.7	0.7	0.7	0	0	0.7	0.7	0.7	0.7	5.6
SCI	0	0.7	0.7	0.9	0.7	0	0	0.9	0.9	0.9	0.7	6.4
CCT	0	0.7	0.7	0.7	0.7	0	0	0.7	0.7	0.7	0.7	5.6
SCP	0	0.7	0.9	0.9	0.7	0	0	0.9	0.7	0.7	0.9	6.4
DOA	0	0.7	0.9	0.9	0.7	0	0	0.9	0.7	0.7	0.9	6.4
IVT	0	0.7	0.9	0.9	0.7	0	0	0.9	0.9	0.9	0.9	6.8
MFM	0	0.7	0.7	0.7	0.7	0	0	0.7	0.7	0.7	0.7	5.6
CRM	0	0.7	0.7	0.7	0.7	0	0	0.7	0.7	0.7	0.7	5.6
SRM	0	0.7	0.9	0.9	0.7	0	0	0.9	0.7	0.7	0.9	6.4
HRM	0	0.7	0.7	0.7	0.7	0	0	0.7	0.7	0.7	0.7	5.6
DEP	0	7.7	8.3	8.9	7.7	0	0	8.9	8.5	8.5	8.3	

DEP: Dependence Power; DRP: Driving Power

3.3.4 Results and Discussions

The results obtained after application of the proposed methodology in the case company are interpreted under two sections (i.e. development of ISM Model and AME classification). Each section is discussed in detail below.

3.3.4.1 Development of ISM model

The diagraph was developed as per the step 6 (Section 3.3.1) and it was further refined to develop ISM model (see Figure 3.2). The developed ISM model was shown and discussed with the experts for its acceptability. The experts had agreed on the developed ISM model. In the current study, AMEs were leveled across five levels in five iterations. ADP, DOA and SCI are at the base of the hierarchy of structural framework (see Figure 3.2). The case company should put effort to acquire capability along these three AMEs which will in turn leads to agility enhancement. The AMEs (i.e. SCP, IVT, MFM, SRM, and HRM) are at IV level. The AMEs positioned in this level should be addressed tactically in the AM implementation process. The AMEs (i.e. PPA, CCT and CRM) are positioned in the level-I and have high dependence power with different driving powers. The AMEs positioned in this level have the long standing and should be treated strategically in order to achieve the excellence in AM implementation. Thus, the ISM model developed presents a directional framework for the case company in successfully implementing AMs and gives clear mental picture of what experts think about the relationship between AMEs.

3.3.4.2 AMEs classification

The classification of AMEs for the case company was carried out through FMICMAC analysis. It is carried out on the basis of driving and dependence powers and all 11AMEs were classified into three clusters (i.e. driver, dependent and linkage quadrant). No AMEs were found in the autonomous quadrant (i.e. low driving and dependence power) and it concludes that all 11 AMEs were relevant for the case company's AM environment.

Driver quadrant (*high driving power, low dependence power*): The AMEs i.e. IVT, DOA, and ADP were in driver/ independent cluster which means that these three AMEs have high influence on rest of the 8 other AMEs and these were also placed on bottom side of the developed ISM. Therefore, these three AMEs have to be addressed at first and the case company should put effort first to enhance them.

Dependent quadrant (l*ow driving power, high dependence power*): The AMEs i.e. PPA, HRM, CRM, CCT and MFM were clustered in the dependent quadrant. This signifies that these AMEs' were mainly dependent on the other AMEs having the capacity to drive the AM. It is not easy to enhance directly but through other AMEs.

Linkage quadrant (*high driving power, high dependence power*): Out of 11 AMEs chosen, 3 AMEs (i.e. SCP, SCI and SRM) were grouped in this cluster having both high driving and high dependence power. Typically these can be attributed as unstable because they have feedback effect i.e. they get affected by their own action and so are difficult to manage. However, these AMEs cannot be ignored and have to be closely monitored regarding their status in making decisions.

3.3.4.3 Selection of AMEs for successful implementation of AM

The IVT, DOA, and ADP were found in driver cluster/quadrant and selected for successful implementation of AM in the case organization. Therefore, these three AMEs have to be addressed at first and the case company should put effort first to enhance them. The Key Performance Indicators (KPIs) were identified for these three selected AMEs and it is mentioned in Table 3.7.

Table 3.7: KPIs for selected AMEs of the case company

Enablers	Key performance indicator
Adaptability	• Responsiveness to technology adoption • Responsiveness to business environments • Responsiveness to customer requirements • Responsiveness to environmental factors • Responsiveness to changes in economic factors • Degree of design flexibility • Level of Infrastructure re-configurability • Creation of fast response teams • Level of operational flexibility • Ability to handle risks
Devolution of Authority	• Organizational structure and culture • Cross functional teams • Level of employee empowerment • Number of brainstorming sessions, quality circle etc • Level of internal consultancy and auditing
Information Visibility and Transparency	• Level of information Accuracy • Level of Information Update • Level of Collaborations • Level of System integration • Degree of business intelligence

The performance of the case company along these KPIs was evaluated and found that their performance needs to be improved. Therefore, it was suggested to adopt benchmarking approach to enhance the performance for these selected three AMEs so that the performances of agility can be improved. The obtained result are for an Indian electrical hardware manufacturing company but the results cannot be too off-mark for other manufacturing companies that are similar in nature. Moreover, the current study may be used as a basis to investigate more details regarding agile manufacturing in general and agile manufacturing enablers in specific.

3.4 Conclusions

The proposed methodology is generic in nature and easy to implement considering multiple experts' judgment. Hence, it can be applied to any manufacturing companies for enhancing its organizational agility capturing the relevant inputs specific to the manufacturing environment. The proposed methodology is applied to an Indian electrical hardware manufacturing company to streamline its efforts so that agility level can be enhanced effectively. The Adaptability (ADP) was concluded as the most influencing AME from the ISM model whereas from FMICMAC analysis, the Devolution of Authority (DOA) along with the other two enablers (i.e. IVT and ADP) were found in driver cluster/quadrant (i.e. high driving and low dependence power). Therefore, these three AMEs were considered as the prerequisite for implementing AM in the case company. The present performance of these three AMEs in the case company was discussed and was found to be reasonably good. But the performance gap exists for all these three AMEs when their performances were compared with their benchmarked values. It was also concluded that a benchmarking model as suggested in the proposed model should be applied to streamline the effort for enhancing the performance of these three AMEs. Although this result was for a case company (i.e. an Indian electrical hardware manufacturing company) but the obtained results cannot be too far from the manufacturing companies similar in nature. Moreover, the current study may be used as a basis to investigate more details regarding agile manufacturing in general and agile manufacturing enablers in specific.

3.4.1 Limitations and Future Research Direction

The implementation study has been carried out for a single manufacturing organization. In future, several case studies could be carried out for different organizations and for different sectors. Like every study, the present study has few shortcomings. However, these shortcomings are the future research directions and these have outlined further research directions in the field of AM in general and AMEs in specific as follows:

- Empirical study on the strength of relationship among AMEs as well as on the agility performance should be carried using structural equation modeling and it should be established in various manufacturing environment. Finally, a theoretical framework should be developed.
- Total Interpretive Structural Modelling (TISM) should be used to study and analyze the linkage relationship between AMEs. Study should be carried out on the quantification of the impact level of each relevant enabler and their combinations on the agility performance. The impact of dynamic behavior of AMEs on agility should also be studied and analyzed using Bayesian networks.
- A complete step by step benchmarking approach should be developed for enhancing its agility in agile manufacturing environment. Study should also be carried out on various implementation issues related to benchmarking approach and strategies should be suggested to mitigate them.

CHAPTER 4

Agile Manufacturing Impediments

4.1 Introduction

In the 21st century, Agile Manufacturing (AM) has gained importance among manufacturers as well as researchers after it was popularized by Iaccoca Institute of Lehigh University, USA in 1991 (Iacocca Institute, 1991). Manufacturers are increasingly adopting AM to fulfill the demanding customer and the volatile market needs. AM is allegedly considered to be the next generation advancement of lean manufacturing. Lean manufacturing focuses only on reducing the costs by removing the wastes while not putting much emphasis on customization, which is the need of the hour. AM makes the organization more flexible and responsive and also keeps the costs as low as possible. Yusuf and Adeleye (2002) empirically established that the agile organizations had better performance criteria in comparison with lean organizations and also concluded that lean organizations have to improve agility level for enhanced competitive advantage. Agility is a system with flexible technology, qualified and trained human resources, and shared information that responds quickly to continuous and unpredicted changes in customers' needs and desires and market demand (Yusuf *et al.*, 1999). AM focuses on prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets (Cho *et al.,* 1996). In manufacturing environment, AM is the antecedent for achieving organizational agility. AM is a paradigm that enables an organization to supply products according to the choice and specifications of the customer (Thilak *et al.*, 2015). It has the ability to thrive in a competitive environment of continuous and unanticipated change and to respond quickly to rapidly changing markets driven by customer-based valuing of products and services (Devor and Mills, 1995). However, adoption of AM is not a trivial task with impediments existing throughout its life cycle spectrum, from development and implementation to its maintenance and improvement phases (Hasan *et al.,* 2007). There exists a need to comprehensively model the agile system by amending the key impediments as well as to find out the interdependency between the agile impediments in an uncertain environment. Therefore, it is essential that the appropriate Agile Manufacturing Impediments (AMIs) should be identified to enhance the agile development in the organizations. But many a times organizations fail to identify the appropriate AMIs due to improper analysis. Thus, considering all the aforementioned issues, this study proposed an approach to identify the appropriate impediments for monitoring the smooth implementation of AM in a specific environment. Investigation of these AMIs is necessary to understand and subjugate them. From our extensive literature review, it is observed that few researches have been undertaken on AMIs related to its identification and contextual relationship (Kamarulzaman *et al.*, 2015; Patil, 2015; Singh *et al.,* 2013; Hasan *et al.*, 2007) (see Table 4.1).

Table 4.1: Literature review on analysis of agile manufacturing Impediments

Author	**Research focus**
Kamarulzaman *et al.*, (2015)	Investigated the obstacles in implementing agility in the Malaysian Palm Oil Industry (MPOI) using mean ranking analysis
Patil (2015)	Proposed ISM method to study the problem of identifying the key agile factors in launching a new product to mass production.
Singh *et al.*, (2013)	Surveyed 102 manufacturing organizations to assess the Impediments to achieve strategic flexibility and establish the relationships among various Impediments using analytical hierarchy process (AHP).
Hasan *et al.*, (2007)	Explored various impediments to adopt AM and established a relationship among the dimensions of impediments through the Interpretive Structural Modelling methodology.

4.2 Literature Review on Agile Manufacturing Impediments

The AMIs are those which impede the successful implementation of AM. On the basis of extensive literature review, 36 AMIs were identified, which act as obstacles for the effective and efficient implementation of AM (see Table 4.2). Again, these 36 impediments are grouped in to 11 main groups (i.e. significant categories). A brief discussion on all eleven significant categories is discussed below.

Table 4.2: Agile manufacturing impediments identified from literature review

Significant Category	**AMI**	**References**
Improper Competency Management [ICM]	Poor core competency	Gunasekaran, 1998, and Gunasekaran and Yusuf, 2002
	Difficulty in adoption of advanced technology	Gunasekaran, 1999, Brown and Bessant, 2003, and Guisinger and Ghorashi, 2004
	Difficulty in change management	BüyüKözkan *et al.,* 2004
Improper Forecast [FOR]	Impact of uncertainty	Cochran *et al.,* 2005
	Improper Assessment of agility	Lin *et al.,* 2006
	Imperfect market knowledge	Narasimhan *et al.,* 2006
Improper Human Resource Management [IHR]	Lack of Human Resource	Sohal, 1999
	Unplanned resource Allocations	Sohal, 1999
	Demotivated resource	Sohal, 1999, and Sumukadas and Sawhney, 2004
	Inadequate trainings	Das, 2001, and Brown and Bessant, 2003
Inefficient Information Management [IIM]	Inadequate information Infrastructure	White *et al.,* 2005
	Inadequate information handling	White *et al.,* 2005
	Inadequate information visibility	White *et al.,* 2005
Lack of Management Involvement [LMI]	Lack of top management commitment	Youssef, 1992, Sohal, 1999, Gunasekaran, 1999, and Hoek *et al*., 2001
	Degree of command and control hierarchy	Hoek *et al.* 2001, and Jin-Hai *et al.,* 2003
	Improper strategic plans	Gunasekaran and Yusuf, 2002
Lack of Manufacturing Flexibility [LMF]	Lack of resource reconfiguration	Gunasekaran (1998)
	Lack of investment in flexible resources	Cochran *et al.*, 2005 and Gunasekaran, 1999
	Ineffective manufacturing control systems	Rao *et al.,* 2006, Backhouse and Burns, 1999, and Yusuf and Adeleye, 2002
	Ineffective manufacturing planning systems	Gunasekaran, 1998, and Yusuf and Adeleye, 2002
	Outdated manufacturing systems	Sohal, 1999, Jin-Hai *et al.,* 2003

Significant Category	**AMI**	**References**
Ineffective Production Planning [IPP]	Operational constraints	Cochran *et al.*, 2005, Youssef, 1992, and Gunasekaran and Yusuf, 2002
	Long time-to-market/ slow new product development	Youssef, 1992 and BüyüKözkan *et al.,* 2004
	Focus on mass production and marketing	Hoek *et al.*, 2001, and Brown and Bessant, 2003
	Low Planning horizons	Brown and Bessant, 2003
	Reluctance to adopt virtual manufacturing	Gunasekaran, 1999
	Overstocking	Koh and Gunasekaran, 2006
External Business Environment [EBE]	Changing customer behavior and expectations	Through discussion held with experts
	Supplier base far from manufacturer	Through discussion held with experts
	Negative Union attitude	Sohal, 1999
	High level of competition	Sohal, 1999
Government Policies and Support [GPS]	Lack of Basic infrastructure	Through discussion held with experts
	Inefficient Legal system	Through discussion held with experts
	High Taxes, Tariffs	Through discussion held with experts
Ineffective Customer Relationship [ICR]	Incomplete customer requirements	Cochran *et al.*, 2005
	Ineffective customer feedback system	Lin *et al.,* 2006
	Lack of responsiveness in capturing customer requirements	Lin *et al.,* 2006
Ineffective Supply Chain [ISC]	Inefficient stakeholder collaborations	Yusuf and Adeleye, 2002, and Pikkarainen and Passoja, 2005
	Inefficient conflicting management styles	Backhouse and Burns, 1999 and Sanchez and Nagi, 2001
	Fail to develop trust	Backhouse and Burns, 1999
	Unbalanced partnerships	Gunasekaran, 1999, Brown and Bessant, 2003, Kohand Gunasekaran, 2006
	Reluctance to form strategic partnerships	Guisinger and Ghorashi, 2004, BüyüKözkan *et al.,* 2004 and Narasimhan *et al.,* 2006

Improper competency management: Manufacturing organization that is not able to leverage or augment its competency will face a difficult task under an uncertain customer demand. It must be open to embrace new technologies and inculcate the change management in order to be agile. Unable to leverage these competencies can impact the agility of organization and erode competiveness. Difficulty in adapting advanced technology and indifference towards adopting changes can be an impediment to agility.

Improper forecast: Improper assessment of uncertainty, market conditions and the degree of agility required will impact the operations and result in inefficient response to customer. Improper assessment of uncertainty can create a false sense of stability. Erroneous market feedback about changes in market situations and inability to estimate the amount of agility required can become an impediment for AM.

Improper human resource management: Good human resource can contribute towards agility if they are trained to become multi-skilled, motivated and placed in the right place and numbers. Untrained and unskilled manpower cannot respond to dynamic changes in manufacturing and hence adversely impact agility. Employees must be motivated to contribute their best and have faith in their work. The demotivated employees are a hurdle in AM. Periodic training in advance technology and practices must be imparted to have highly skilled work force. Inability to maintain proper training schedules results in an impediment to agility.

Inefficient information management: It is related to non-transparency in information sharing in terms of time, accuracy, nature and visibility. Inadequate information sharing is a failure in capturing and managing the information on real time basis. Inadequate visibility of real time information in right form and accuracy is the antecedent for agility in the organization.

Lack of management involvement: Top management support and involvement in maintaining an agile conducive environment will lead to an agile organization. Following adverse strategic plans like competing based on cost and price, only goodwill without importance to customer expectations contradicts the agile philosophy. A management without proper strategy, commitment and plans will fail to leverage the opportunities. Intermittent support for agility along various dimensions is impediments for AM. Delay in taking quick decisions due to different levels of hierarchy and conflicts which in turn reduces the agility of organization.

Lack of manufacturing flexibility: Manufacturing process is the backbone of any agile organization. The manufacturing processes using advanced technologies and equipment will be in a better position to display agility. Flexible equipment and reconfigurability are the key areas that promote agility. Lack of resource reconfiguration means inability to reconfigure the available recourses to adapt to new manufacturing processes. Investing in inflexible SPMs (Special Purpose Machines) and special technologies restricts the range of operations and makes manufacturing processes rigid and inflexible. Manufacturing control systems that do not support quick reorientation and dynamic changes in processes are an impediment to AM. Inability to plan for variable product processes and concentrating on few product types impacts flexibility. Use of outdated machinery and technology results in low productivity and shows poor responsiveness.

Ineffective production planning: Operations planning keeping in view of the changing market conditions and customer preferences are the need for an agile organization. When the planning is bogged down by internal constraints that restrict proper planning and strategies that are based on mass production and marketing, will result in a negative impact on the agility of the organization. Operational constraints can disrupt production plans and impact the agility of organization. Inability to deliver product from “conception to sales” in shortest possible time impacts the competitiveness and reduces agility. Planning based on mass production, customization and mass marketing steers the organization away from being agile. There must not be any restriction on range and depth of planning while considering the products and product varieties. Inability to leverage the virtual manufacturing concept in planning results in large production times that impacts the agility. Concept of overstocking to become agile is counterproductive as it does not consider the changing customer requirements.

External business environment: The agility level is affected by external business environment created due to customer, supplier, unions and competitors. When the union dictates what and how the work is to be done, it reduces the flexibility of organizational attitude towards business in general and agility in specific. Supplier base far from manufacturer also reduces the flexibility of the organization.

Government policies and support: Government policies and support includes providing basic transportation system, energy, water and security.

Adverse policies like high taxes, stricter pollution control norms, delays in granting licenses for expansion or extensions, biased trade policies etc., derail agility.

Ineffective customer relationship: Better customer relations are necessary to understand their requirements, feedbacks and to address their grievances on time, which in turn will enhance agility the organization. Inaccurate and incomplete information regarding customers' requirements impacts the ability of organization to provide desired product. Improper customer feedback can result in erroneous data being used for analysis.

Ineffective supply chain: Collaboration among strategic supply chain partners is the key to be agile. Where the relationship is not nurtured or sustained due to differences in opinions, management or competency, it is difficult to operate as a team and be on schedule. This results in an organization losing its agility. Inefficient and conflicting management system for decision making and management of activities among the supply chain members reduces cooperation and transparency in operations and then by reduces agility. Failure to develop trust among strategic supply chain members hampers collaboration and agility. Partnerships that do not complement each other can create drift in the operations which in turn delay the production. Reluctance to form partnerships to derive synergy in the long run may become hindrance for a good partnership.

4.3 Proposed Methodologies for analyzing Manufacturing Impediments

Two methods have been proposed to analyze the AMIs. The first method uses Fuzzy DEMATEL to identify the AMIs based on cause and effect grouping and the influence of impediments on other impediments to estimate the criteria weights. No literatures have appeared on cause and effect analysis among the impediments. Therefore, a generic methodology is proposed using fuzzy DEMATEL to establish relationship among AMIs (i.e. cause and effect), determine the strength and develop impact-relationship map. The proposed methodology is applied to an Indian Automobile manufacturing company to understand the salient features of the concept. This methodology is explained in the Section 4.3.1.

The other method uses ISM – FMICMAC method to identify the right set of significant categories of AMIs on which an organization should put effort to enhance the performance of it. This method is explained in the Section 4.4. It is essential that the appropriate set of significant categories of AMIs should be identified to enhance the agile development in the organization. But many a times organizations fail to identify these appropriate set of significant categories of AMIs due to improper analysis. Thus, this study proposed an approach to identify the appropriate set of significant categories of AMIs for monitoring the smooth implementation AM in a specific environment.

4.3.1 Proposed Methodology for Analyzing the Agile Manufacturing Impediments

A methodology using fuzzy DEMATEL is proposed to analyze the AMIs to mitigate their impact for successful implementation of AM. DEMATEL was first proposed by Battelle Memorial Institute of Geneva Research Centre. DEMATEL captures the relationship and divides the criteria into two groups, particularly, the cause group and the effect group and to find out the influence of the cause group on the effect group where such influence is used to estimate the criteria weights (Dalalah *et al.*, 2011). It is an effective procedure for analyzing the structure and relationships between numbers of available alternatives. DEMATEL can prioritize the criteria based on the type of relationships and severity of the influences on each other (Tseng and Lin, 2009). Alternatives having more severity of influence on another are assumed to have higher priority and are called cause criteria. And those receiving more influence from another are assumed to have lower priority and are called effect criteria (Seyed-Hosseini *et al.*, 2006). This model is useful for visualizing the structure of complex causal relationships with matrices or digraphs among multiple factors. Many researchers have used the fuzzy DEMATEL in their research spanning over the area of supplier development program (Routroy and Sunil, 2014), knowledge management adoption in supply chain (Patiland Kant, 2014), supplier selection (Chang *et al.*, 2011), service quality expectation (Tseng, 2009), emergency management (Zhou *et al.,* 2011), municipal solid waste management in Metro Manila (Tseng and Lin, 2009) and Customers' Choice Behavior Model (Chen-Yi *et al.*, 2007). The notations used in the fuzzy DEMATEL are mentioned below.

$\boldsymbol{F}$:	Fuzzified Direct Relationship Matrix (FDRM)
$F_{ij} = (l_{ij}, m_{ij}, r_{ij})$:	Elemental value of FDRM, where it indicates the degree that a criterion i influences criterion j
$(xl_{ij}, xm_{ij}, xr_{ij})$:	Normalized value of (l_{ij}, m_{ij}, r_{ij})
$min\ l_{ij}$:	Column wise minimum l_{ij}
$max\ r_{ij}$:	Column wise maximum r_{ij}
xls_{ij}:	Left spread measure of normalized fuzzy number

xrs_{ij}:	Right spread measure of normalized fuzzy number
x_{ij}:	Total normalized crisp value calculated from left and right spread measures of normalized fuzzy numbers
z_{ij} :	Crisp value defuzzified from triangular fuzzy number
z^k:	Defuzzified matrix obtained from the k^{th} expert
h:	Number of experts
n:	Number of criteria
$T=t_{ij}$:	Total Relation Matrix (TRM)
$A=a_{ij}$:	Average Direct Relationship Matrix (ADRM)
$\max\limits_{1\le i\le n} \sum\limits_{j=1}^{n} a_{ij}$:	Total direct influence of the criteria on other criteria
$\max\limits_{1\le j\le n} \sum\limits_{i=1}^{n} a_{ij}$:	Total direct influence received from other criteria
R:	Vector of length n representing rows sum of the TRM
C:	Vector of length n representing columns sum of the TRM

For the detail step by step algorithm, one can see in the Figure 4.1. Each step used is discussed below.

Step 1: *Define the manufacturing environment*

AM is being adopted by manufacturers for dramatic performance enhancements to become national and international leaders in an increasingly competitive market of fast changing customer requirements (Yusuf *et al.*, 1999). AM requires enriching of the customer, co-operating with competitors, organizing to manage change, uncertainty and complexity, and leveraging people and information (Gunasekaran, 1999). The attributes of AM like innovation, superior quality, responsiveness, new product introduction is given importance while defining the environment.

Step 2: *Identification of specific set of AMIs*

Here, impediments of AM are considered to be the evaluation criteria for this proposed methodology. The AMI's are to be identified through literature review, brain storming sessions and discussions with industrial experts, researchers and academicians. Again, the relevant AMIs particular to the case company is to be sorted out from the generic set of impediments.

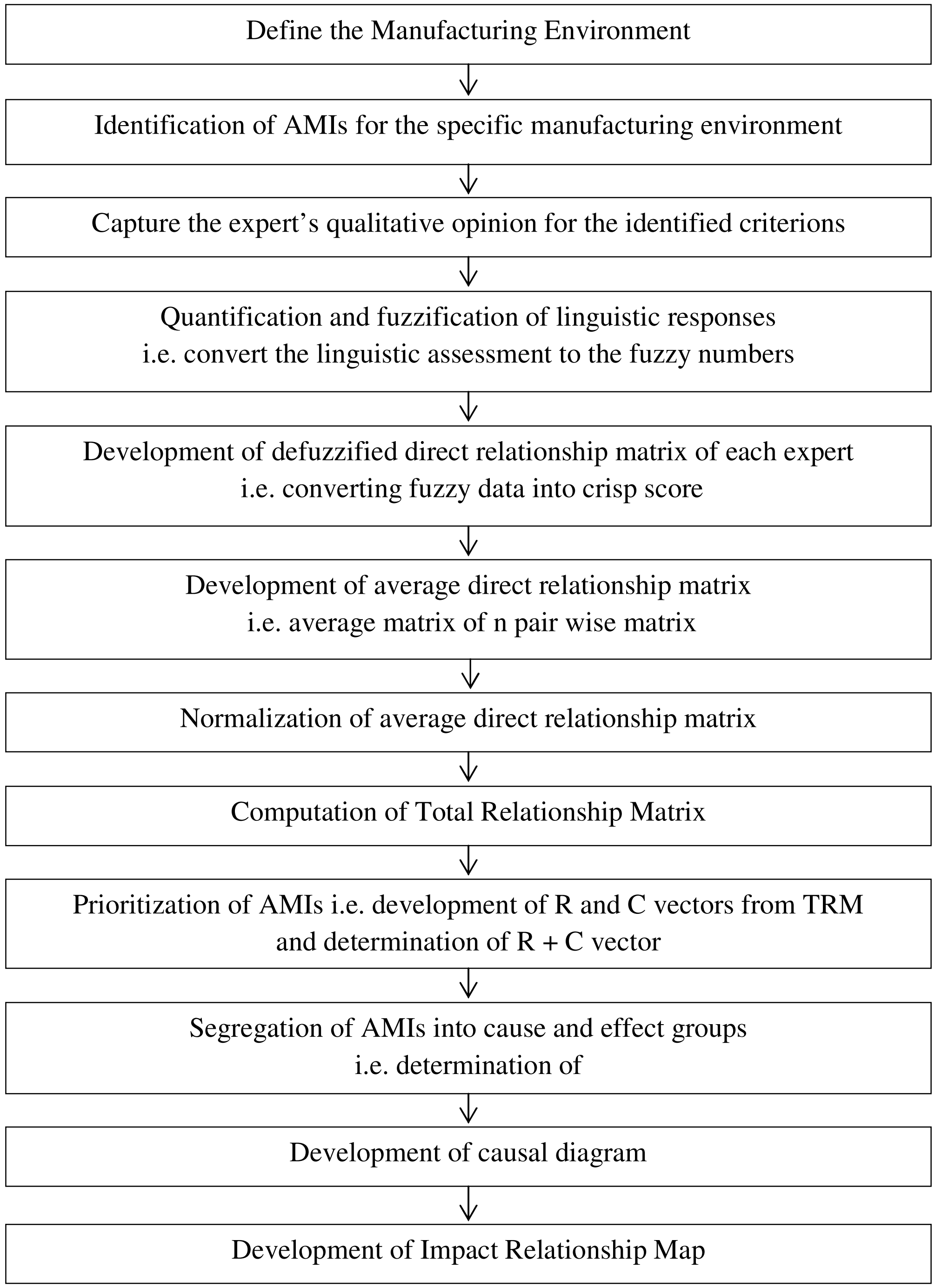

Figure 4.1: Proposed methodology for analyzing AMIs

Step 3: *Capture the expert's qualitative opinion for the identified AMIs*

The expert's qualitative opinions regarding mutual influence of the relevant AMIs identified from previous steps should be captured using pair wise comparison matrix. These pair wise comparisons should be carried out using linguistic variables i.e. low, medium, high and very high influence as given in Table 4.3.

Table 4.3: Quantification and fuzzification scale for linguistic responses

Linguistic terms	Influence score	Triangular fuzzy numbers
No Influence (No)	0	(0, 0, 0.25)
Very low influence (VL)	1	(0, 0.25, 0.50)
Low influence (L)	2	(0.25, 0.50, 0.75)
High influence (H)	3	(0.50, 0.75, 1.00)
Very high influence (VH)	4	(0.75, 1.00, 1.00)

Step 4: *Quantification and fuzzification of linguistic responses*

Pair-wise comparison matrices are to be developed for the AMIs by taking the expert's qualitative opinions in terms of linguistic responses. These linguistic responses are to be transformed in to a scale of 0-4 to get the quantified direct relationship matrices. Subsequently, fuzzify the matrices to capture the uncertainty in the experts' opinions such that the results obtained are much more accurate. To develop fuzzified direct relationship matrices, convert the influence scores assigned to the linguistic variables into triangular fuzzy numbers as mentioned in Table 4.3.

Step 5: *Development of defuzzified direct relationship matrix of each expert*

Develop the Defuzzified Direct Relationship Matrix (DDRM) for each expert using converting the Fuzzy data into Crisp Scores (CFCS) method (Opricovic and Tzeng, 2003). The details of CFCS are mentioned below:

(i) Normalization:

$$xr_{ij} = \left(r_{ij} - \min l_{ij}\right) / \Delta_{\min}^{\max}$$

$$xm_{ij} = \left(m_{ij} - \min l_{ij}\right) / \Delta_{\min}^{\max}$$

$$xl_{ij} = \left(l_{ij} - \min l_{ij}\right) / \Delta_{\min}^{\max}$$

where $\Delta_{\min}^{\max} = \max r_{ij} - \min l_{ij}$

(ii) Left and right spread measures of normalized fuzzy numbers,

$$xrs_{ij} = xr_{ij} / \left(1 + xr_{ij} - xm_{ij}\right)$$

$$xls_{ij} = xm_{ij} / \left(1 + xm_{ij} - xl_{ij}\right)$$

(iii) Compute total normalized crisp score

$$x_{ij} = \frac{\left[xls_{ij}\left(1 - xls_{ij}\right) + xrs_{ij} \times xrs_{ij}\right]}{\left(1 - xls_{ij} + xrs_{ij}\right)}$$

(iv) Compute crisp value

$$z_{ij} = \min l_{ij} + xr_{ij} \times \Delta_{\min}^{\max}$$

Step 6: *Development of average direct relationship matrix (ADRM)*

Calculate the ADRM by taking the average of all "*h*" DRMs (where *h* is the number of experts). If $z^1, z^2, z^3, ..., z^h$ are the DDRMs obtained then ADRM (A) is obtained as shown below

$$A = \frac{\left(\sum_{k=1}^{h} z^k\right)}{h}$$

The ADRM elemental values can be represented as $A = \left[a_{ij}\right]_{n \times n}$

Step 7: Normalization *of average direct relationship matrix*

The normalized ADRM is denoted as *D*. It is calculated as follows

$$D = \frac{A}{S}$$

where $s = \max\left(\max_{1 \le i \le n} \sum_{j=1}^{n} a_{ij} \quad \max_{1 \le j \le n} \sum_{i=1}^{n} a_{ij}\right)$

Step 8: *Computation of total relation matrix*

$$T = D(I - D)^{-1} \text{ where, } I \text{ is the identity matrix.}$$

$$T = \left[t_{ij}\right]_{n \times n}$$

Step 9: *Prioritization (i.e. degree of importance) of AMIs*

From the total relation matrix (*T*) obtained in the previous step, *R* and *C* vectors are formed. *R* represents the row sum of matrix *T*:

$$R = \left[\sum_{i=1}^{n} t_{i1} \sum_{i=1}^{n} t_{i2} \ldots \sum_{i=1}^{n} t_{ij} \ldots \sum_{i=1}^{n} t_{in}\right]$$

(where, *j* represents the row number, *i* represents column number and *n* represents number of rows or columns of matrix *T*, since *T* is a square matrix). Similarly, *C* represents column sum of matrix *T*:

$$C = \left[\sum_{j=1}^{n} t_{i1} \sum_{j=1}^{n} t_{i2} \ldots \sum_{j=1}^{n} t_{ij} \ldots \sum_{j=1}^{n} t_{in} \right]$$

From R and C vectors, determine the $R + C$ vector (where each element of the vector indicates the degree of importance of the corresponding enabler) and prioritize the enablers.

Step 10: *Segregation of AMIs into cause and effect groups*

Determine the $R - C$ vector from R and C vectors obtained in the previous step. The positive signed elements indicate that the corresponding AMIs are causes and negative AMIs indicate effects.

Step 11: *Development of causal diagram*

Develop a causal diagram for the AMIs taking their $R + C$ and $R - C$ values along X-axis and Y-axis respectively.

Step 12: *Development of impact relationship map*

On the basis of experts' opinion, set the threshold value for developing impact relationship map. This threshold value filters out insignificant interdependent relationships between AMIs. It is deducted from all the elements of TRM and then the relationships between AMIs having negative values are ignored to determine the reduced TRM. This reduced TRM forms the basis for developing the impact relationship map.

4.3.2 Application of the Proposed Methodology for An Indian Automobile Manufacturing Company

The proposed methodology was applied to an Indian automobile manufacturing company for analyzing the AMIs. As per the company's policy, to protect its confidentiality and to maintain good relationship with the company and to conduct further research, name of the company is not disclosed and it is named as 'case company'. The case company is a large scale automobile manufacturer. The company has pioneered in operations with over 20 years of manufacturing expertise in developing the flexibility to cater to any volume demand from the customer. No matter what the intricacy levels of product manufacturing, the company has always found innovative ways and technologies to make or source the product. With a demand of half a million plus vehicles, it became imperative for the company to have robust processes to support AM. After holding detailed discussions with the top management and the people responsible for implementing AM, they agreed to extend their cooperation by providing necessary inputs. Each AMI is discussed with the experts and their inputs were recorded. These are discussed below in a systematic manner. The case company faces delay in launch of new models due to small in house Research and Development (R&D) capabilities which reveals its poor core competency. Employees are ready to take initiatives in the company but any changes in initial desired state needs thorough discussion following a hierarchy approach makes it difficult to change. The case company has shortage of skilled manpower which leads to longer training periods for the subordinates. There is an inadequate information visibility as each separate function has a specific information technology (IT) support and information flow which is not streamlined due to access issues and confidentiality. Decision making through hierarchal approach has always resulted in delay in projects. Lack of resource reconfiguration like absence of single minute exchange of dies (SMEDs) is leading to longer setup times and less standard platforms increasing the complexity of manufacturing.

A large portion of manufacturing is outsourced for the case company. Vendors operate on very thin margins so buying sophisticated machinery is out of bounds for the case company. There are lots of operational constraints like production capacity constraints due to space restrictions, government policies on labour and environmental compliance are acting as an impediment for the case company. Concept of virtual manufacturing is not prevalent in the organization. Teams of experts are working on conceptualizing this process in the next couple of years. Sometimes fixed duration of tax incentives forces the company to have capacity constraints for a particular manufacturing location. The customer feedback system is not much effective due to lack of proper channel to address market feedback. The case company has recently started developing in house R&D capability to capture the customer requirements in a time bound manner. Due to inefficient stakeholder collaboration, negotiation on product/component price takes a lot of time. There exists a disconnection between Enterprise Resource Planning (ERP) and Manufacturing Resource Planning (MRP) software between the original equipment manufacturer which leads to the wrong planning and delivery form the customers. Improper market knowledge also acts as an impediment for the case company. Because of the absence of fool-proof mechanism information handling is not completely efficient. Top management of the company has very less involvement in mentoring various programs. The strategic plan of the case company has changed from time to time due to the merger and demerger of the company. It is found that, 70% of the supplier base is also far from the manufacturer which acts a major impediment in the implementation of AM. Out of generic set of AMIs, the above information has been noticed while discussing with the team of experts and the relevant AMIs were identified as mentioned in Table 4.4. There are also 16 AMIs which are found to be irrelevant for the case company as the company has achieved significant milestones in these aspects. These are discussed systematically in the below paragraph.

Table 4.4: Selected agile manufacturing impediments

Impediments	**Abbreviation**	**Description**
Poor core competency	PCC	Unable to leverage the competencies can impact the agility of organization and erodes competiveness.
Difficulty in change management	DCM	Indifferent attitude towards adopting changes is an impediment to AM.
Lack of Human Resource	LHR	Untrained and unskilled manpower cannot respond to dynamic changes in manufacturing and hence impact agility.
Inadequate information visibility	IIV	Invisibility of information on real time in right form with accuracy.
Degree of command and control hierarchy	DCC	Delay in taking quick decisions due to different levels of hierarchy and conflicts which in turn reduces the agility of organization.
Lack of resource reconfiguration	LRR	It indicates the inability to reconfigure the available recourses for adapting new manufacturing processes.
Lack of investment in flexible resources	LFR	Investing in inflexible SPMs (Special Purpose Machines What is SPMs) and special technologies restricts the range of operations and makes manufacturing processes rigid and inflexible.
Operational constraints	OCO	Operational constraints can disrupt production plans and impact the agility of organization.
Reluctance to adopt virtual manufacturing	RVM	It indicates inability to leverage the virtual manufacturing concept in planning results in large production times - impacting agility.

Impediments	**Abbreviation**	**Description**
High Taxes, tariffs	HTT	It indicates level of taxes and tariffs present in the business environment.
Ineffective customer feedback system	ICF	Improper customer feedback can result in erroneous data being used for analysis.
Lack of responsiveness in capturing customer requirements	LCC	It indicates improper capturing of real time customer data and not able to satisfy customer requirement.
Inefficient stakeholder collaborations	ISC	Collaborations with various stakeholders in the supply chain must to be flexible and agile.
Inefficient conflicting management styles	ICC	Inefficient conflicting management system for decision making and management of activities among the supply chain members reduces cooperation and transparency in operations - reducing agility.
Imperfect market knowledge	IMF	Erroneous market feedback about changes in market situations can impact agility.
Inadequate information Infrastructure	III	It is related to improper transparence in information sharing in terms of time, accuracy, nature/type visibility etc.
Inadequate information handling	IIH	Improper capturing on real time basis .
Lack of top management commitment	LTP	Intermittent support for agility along various dimensions is impediments for AM.
Improper strategic plan	ISP	Following adverse strategic plans like competing based on cost and price, only goodwill without importance to customer expectations contradicts the agile philosophy.
Supplier base far from manufacturer	SBM	Suppliers are far from manufacturing base.

The case company is very open to advanced technology adoption provided there is a market demand for it and it is viable for the company. As the company mainly focuses on automotive segment which demand is easy to forecast in a short term as well as long term, so the impact uncertainty generally does not affect the company. The case company is already practicing the lean production system and has a right mix of contract and permanent labour, which enables the company for proper resource allocation. In order to motivate the workforce, top management always praises the good work and pays a very good salary in comparison to other companies in the same segment. Need based training is being provided to the workforce from time to time. The case company has implemented product life cycle monitoring software and cost control measures to get continuous feedback for quickly addressing the dynamic changes in the processes. Presence of strong support from ERP and MRP software for monitoring planning and scheduling of raw material, tooling etc. has given significant flexibility to accommodate new processes in the company. The case company provides financial and capability support to vendors for dedicated lines in the plant. It has long range forecast to weekly forecasting plans according to that the stocking policies both In-plant and dealer was set to be 1 day and 4 weeks. A strong market share of more than 50% was captured by the company while on the same time other competitors are struggling far behind. Most of the plants of the company are situated in northern region of India which is well connected thorough road and railway networks and also major ports in western region of India helps the company to maintain a good transportation network. After gaining thorough understanding of company's environment, finally 20 AMIs were identified which are found to be relevant to the case company. Eleven experts (with a minimum experience of 7 years in the case company) were drawn for further analysis of the AMIs. Eleven experts' qualitative opinions regarding mutual influence of the selected twenty AMIs were compared using linguistic variables (i.e. no, low, medium, high and very high influence) to obtain pair wise comparison matrix. Table 4.5 shows the linguistic response matrix collected from the 6^{th} expert. These eleven linguistic response matrices were used as inputs to a user-friendly program developed in MATLAB for implementing fuzzy DEMATEL algorithm. In the program, the linguistic response matrices from all eleven experts were quantified to obtain direct relationship matrices. The direct relationship matrix of each expert had been fuzzified to develop FDRM on the basis of Table 4.3. The FDRM had been defuzzified using a defuzzification technique to obtain DDRM for each expert. All the obtained eleven DDRMs were averaged to form ADRM.

Table 4.5: Linguistic response matrix of the sixth expert

	PCC	**DC M**	**LHR**	**IIV**	**DCC**	**LRR**	**LFR**	**OC O**	**RV M**	**HTT**	**ICF**	**LCC**	**ISC**	**ICC**	**IMF**	**III**	**IIH**	**LTP**	**ISP**	**SBM**
PCC	0	H	VL	L	L	H	L	VL	L	No	L	H	VH	L	VL	L	L	No	No	No
DCM	H	0	No	No	No	VL	VL	No	L	No	L	L	VL	VL	No	No	VL	VL	VL	No
LHR	VH	H	0	No	L	L	L	L	H	No	VH	VH	VL	No	No	No	H	No	L	No
IIV	VH	VL	No	0	VL	H	H	H	No	No	VH	VH	VH	VH	VH	No	L	No	VL	No
DCC	L	H	L	VH	0	L	L	H	L	No	No	No	No	No	VL	No	L	No	No	No
LRR	VL	H	VH	No	No	0	L	H	L	No	L	L	No	No	L	H	L	No	No	No
LFR	VH	L	VH	No	No	L	0	H	H	No	H	VH	L	VL	H	H	H	No	VH	No
OCO	H	H	H	No	No	VL	L	0	No	No	H	H	No	H	L	No	L	No	VL	No
RVM	VH	H	No	VH	No	L	H	H	0	No	No	VH	H	No	No	VH	VH	No	No	No
HTT	No	VL	No	No	No	H	L	L	VL	0	No	No	VL	No	No	No	No	No	No	VL
ICF	VL	No	VL	No	L	No	VL	VL	No	No	0	VH	VL	VL	VH	L	L	No	No	No
LCC	VL	No	VL	No	H	No	L	VL	L	No	H	0	H	VL	L	L	VH	No	L	VL
ISC	L	VH	H	L	L	L	VH	H	VH	No	H	No	0	H	L	VH	VL	VL	No	No
ICC	VH	H	H	H	No	L	No	L	VL	No	No	L	L	0	VL	No	H	VL	VH	No
IMF	VH	L	L	No	No	L	VL	L	L	No	VH	H	No	L	0	VH	VH	VL	L	VL
III	H	H	L	VH	No	L	VL	H	VH	No	H	No	H	L	L	0	VH	VL	VL	No
IIH	VH	H	No	L	H	No	No	L	L	No	H	VH	VH	H	L	VL	0	VH	L	VL
LTP	VH	H	VH	H	L	VH	VH	L	VH	No	L	H	H	No	VL	No	VH	0	L	No
ISP	VH	VH	VH	H	L	H	L	H	H	No	H	H	VL	VL	L	VL	No	L	0	VL
SBM	H	H	No	L	No	L	L	L	No	No	No	VH	L	No	L	H	VL	No	VL	0

The normalized ADRM and TRM had been calculated and are mentioned in Table 4.6 and Table 4.7 respectively. The R vector (see Table 4.8) and C vector (see Table 4.8) were calculated in order to determine $R+C$ vector (see Table 4.8) and $R-C$ vector (see Table 4.8). The prioritization (i.e. degree of importance) of AMIs is obtained from $R+C$ vector while the segregation of AMIs into cause and effect groups is carried out on the basis of $R-C$ vector (see Table 4.9 and Table 4.10). The causal diagram (see Figure 4.2) had been plotted to know the distribution of AMIs with respect to degree of importance and degree of cause or effect. The threshold value was fixed as 0.0172 (the average of TRM) on the basis of eleven experts' judgment. This threshold value is deducted from all the matrix elements of TRM to obtain significant TRM. In the significant TRM all those which are negative represents those elemental values of TRM which are less than the threshold value and they can be safely eliminated to obtain reduced TRM (see Table 4.11). The strength of influencing on and influenced by other AMIs for each AMI can be retrieved from reduced TRM (see Table 4.11). In order to present this, the strength of influencing on and influenced by other AMIs for IIV is shown in Table 4.12. The prominent influencing on and influenced by other AMIs for each AMI is determined by Pareto analysis and is presented in Table 4.13 and Table 4.14 respectively. This reduced TRM also forms the basis for developing the impact relationship map.

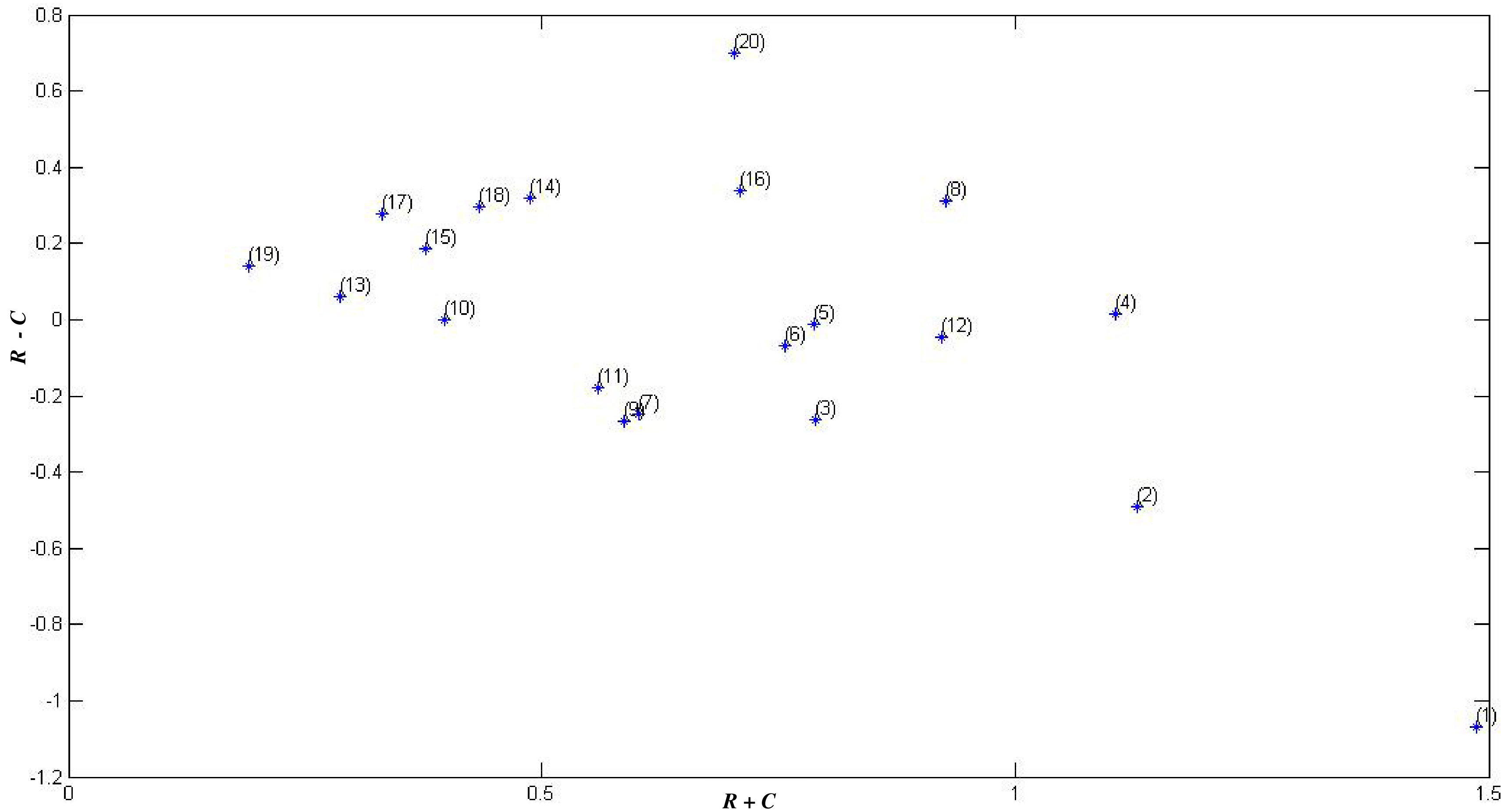

Figure 4.2: Causal diagram of agile manufacturing impediments

Table 4.6: Average defuzzified direct relationship matrix

	PCC	DCM	LHR	IIV	DCC	LRR	LFR	OCO	RVM	HTT	ICF	LCC	ISC	ICC	IMF	III	IIH	LTP	ISP	SBM
PCC	0.0333	0.9242	0.0000	0.0000	0.0333	0.0000	0.0333	0.0000	0.0000	0.0000	0.0000	0.9242	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0333	0.0000
DCM	0.7333	0.0333	0.7333	0.0000	0.0000	0.0333	0.0000	0.0000	0.9455	0.5212	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000
LHR	0.9667	0.0000	0.0000	0.7121	0.0000	0.0000	0.0000	0.6909	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0333	0.0000	0.0000	0.0000
IIV	0.9242	0.0333	0.0333	0.9667	0.4788	0.6909	0.0000	0.5212	0.0000	0.0000	0.9667	0.5424	0.0000	0.0000	0.0000	0.2879	0.0333	0.0000	0.0000	0.0000
DCC	0.5000	0.0333	0.5212	0.5212	0.7121	0.3091	0.0000	0.0000	0.9455	0.0000	0.0000	0.0333	0.0000	0.0000	0.5212	0.0000	0.0000	0.0000	0.0000	0.0000
LRR	0.3303	0.9242	0.0000	0.0333	0.0000	0.0000	0.9455	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3091	0.0000	0.9455	0.0000	0.0000	0.0000	0.0000
LFR	0.9030	0.0333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7121	0.0000	0.0000	0.2879	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
OCO	0.7545	0.7545	0.5000	0.5000	0.2879	0.9030	0.7121	0.0000	0.5212	0.0000	0.7121	0.7333	0.0000	0.0000	0.0333	0.0000	0.0000	0.0000	0.0000	0.0000
RVM	0.9667	0.0000	0.0333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0333	0.0000	0.7121	0.0000	0.0000	0.0000	0.0333	0.0000	0.0000	0.0000	0.0000	0.0000
HTT	0.0333	0.5424	0.0333	0.0333	0.5212	0.0333	0.0333	0.0333	0.0333	0.0333	0.5424	0.0000	0.0000	0.3091	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ICF	0.2879	0.0000	0.0333	0.0000	0.9030	0.0000	0.0000	0.0000	0.7333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LCC	0.2667	0.7121	0.5000	0.7121	0.0000	0.3091	0.7333	0.7545	0.0000	0.0333	0.0000	0.0000	0.0333	0.2879	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISC	0.4788	0.2879	0.0000	0.0000	0.0000	0.0000	0.5212	0.5424	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ICC	0.9242	0.7333	0.9455	0.0000	0.0000	0.7121	0.0000	0.0333	0.0000	0.0000	0.0000	0.7333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
IMF	0.9455	0.0333	0.4788	0.0333	0.5212	0.0000	0.5000	0.0000	0.0000	0.0333	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
III	0.7545	0.7333	0.7333	0.7333	0.5212	0.0000	0.4788	0.0333	0.7121	0.0333	0.7121	0.0000	0.0333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
IIH	0.9455	0.0000	0.9455	0.3091	0.0000	0.9455	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LTP	0.9242	0.9667	0.0000	0.5000	0.0333	0.0000	0.0000	0.0000	0.0000	0.5212	0.0000	0.7333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISP	0.9667	0.6909	0.0000	0.0000	0.0333	0.0333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SBM	0.7121	0.7121	0.0333	0.5636	0.0333	0.5212	0.4788	0.5000	0.0333	0.0333	0.0333	0.9242	0.5424	0.0333	0.5000	0.7121	0.3303	0.0333	0.3091	0.0333

Table 4.7: Total relationship matrix

	PCC	DCM	LHR	IIV	DCC	LRR	LFR	OCO	RVM	HTT	ICF	LCC	ISC	ICC	IMF	III	IIH	LTP	ISP	SBM
PCC	0.0108	0.0750	0.0072	0.0049	0.0032	0.0026	0.0069	0.0046	0.0058	0.0036	0.0011	0.0707	0.0003	0.0017	0.0002	0.0003	0.0000	0.0028	0.0025	0.0000
DCM	0.0692	0.0127	0.0566	0.0056	0.0027	0.0035	0.0011	0.0037	0.0727	0.0412	0.0062	0.0074	0.0001	0.0012	0.0003	0.0004	0.0002	0.0379	0.0002	0.0000
LHR	0.0825	0.0103	0.0037	0.0610	0.0044	0.0075	0.0044	0.0550	0.0037	0.0007	0.0077	0.0113	0.0001	0.0004	0.0003	0.0018	0.0027	0.0004	0.0002	0.0000
IIV	0.0903	0.0207	0.0118	0.0877	0.0498	0.0622	0.0111	0.0462	0.0129	0.0016	0.0835	0.0533	0.0005	0.0026	0.0021	0.0279	0.0027	0.0008	0.0002	0.0000
DCC	0.0574	0.0099	0.0445	0.0483	0.0609	0.0277	0.0046	0.0048	0.0768	0.0008	0.0080	0.0089	0.0017	0.0009	0.0416	0.0030	0.0002	0.0004	0.0001	0.0000
LRR	0.0427	0.0788	0.0104	0.0082	0.0041	0.0022	0.0741	0.0015	0.0101	0.0074	0.0053	0.0048	0.0018	0.0235	0.0002	0.0711	0.0000	0.0030	0.0001	0.0000
LFR	0.0701	0.0106	0.0012	0.0007	0.0026	0.0005	0.0016	0.0014	0.0013	0.0540	0.0024	0.0051	0.0216	0.0014	0.0001	0.0001	0.0000	0.0004	0.0002	0.0000
OCO	0.0825	0.0727	0.0464	0.0490	0.0301	0.0733	0.0631	0.0080	0.0504	0.0065	0.0606	0.0635	0.0017	0.0032	0.0038	0.0062	0.0002	0.0027	0.0002	0.0000
RVM	0.0754	0.0056	0.0034	0.0007	0.0042	0.0003	0.0006	0.0005	0.0062	0.0003	0.0538	0.0053	0.0001	0.0001	0.0027	0.0000	0.0000	0.0002	0.0002	0.0000
HTT	0.0119	0.0440	0.0088	0.0055	0.0448	0.0055	0.0033	0.0034	0.0113	0.0045	0.0420	0.0027	0.0001	0.0234	0.0018	0.0005	0.0000	0.0016	0.0000	0.0000
ICF	0.0300	0.0026	0.0059	0.0036	0.0721	0.0020	0.0005	0.0006	0.0606	0.0001	0.0035	0.0024	0.0001	0.0001	0.0030	0.0002	0.0000	0.0001	0.0001	0.0000
LCC	0.0432	0.0652	0.0460	0.0639	0.0051	0.0324	0.0615	0.0622	0.0081	0.0085	0.0089	0.0104	0.0039	0.0227	0.0004	0.0037	0.0003	0.0024	0.0001	0.0000
ISC	0.0438	0.0279	0.0034	0.0023	0.0015	0.0032	0.0419	0.0412	0.0039	0.0034	0.0027	0.0055	0.0009	0.0003	0.0002	0.0003	0.0000	0.0010	0.0001	0.0000
ICC	0.0845	0.0695	0.0779	0.0090	0.0013	0.0563	0.0083	0.0104	0.0058	0.0034	0.0019	0.0620	0.0003	0.0027	0.0001	0.0042	0.0002	0.0026	0.0002	0.0000
IMF	0.0815	0.0102	0.0386	0.0073	0.0422	0.0018	0.0399	0.0042	0.0040	0.0051	0.0012	0.0063	0.0384	0.0003	0.0017	0.0003	0.0001	0.0004	0.0002	0.0000
III	0.0811	0.0631	0.0617	0.0660	0.0491	0.0056	0.0377	0.0089	0.0653	0.0071	0.0625	0.0091	0.0034	0.0005	0.0021	0.0018	0.0003	0.0024	0.0002	0.0000
IIH	0.0825	0.0121	0.0726	0.0304	0.0020	0.0731	0.0063	0.0054	0.0017	0.0009	0.0029	0.0074	0.0002	0.0019	0.0001	0.0058	0.0003	0.0005	0.0002	0.0000
LTP	0.0813	0.0846	0.0080	0.0453	0.0070	0.0048	0.0045	0.0059	0.0072	0.0430	0.0058	0.0630	0.0003	0.0025	0.0003	0.0013	0.0001	0.0032	0.0002	0.0000
ISP	0.0770	0.0581	0.0036	0.0008	0.0030	0.0029	0.0008	0.0005	0.0044	0.0024	0.0004	0.0055	0.0000	0.0002	0.0001	0.0002	0.0000	0.0022	0.0002	0.0000
SBM	0.0859	0.0769	0.0190	0.0583	0.0115	0.0498	0.0519	0.0473	0.0145	0.0089	0.0135	0.0809	0.0436	0.0056	0.0381	0.0583	0.0250	0.0054	0.0234	0.0025

Table 4.8: Prioritization of agile manufacturing impediments

	PCC	DCM	LHR	IIV	DCC	LRR	LFR	OCO	RVM	HTT	ICF	LCC	ISC	ICC	IMF	III	IIH	LTP	ISP	SBM
R	0.2042	0.3227	0.2581	0.5678	0.4005	0.3491	0.1751	0.6242	0.1598	0.2154	0.1875	0.4491	0.1836	0.4007	0.2836	0.5280	0.3062	0.3684	0.1625	0.7205
C	1.2837	0.8106	0.5308	0.5585	0.4016	0.4172	0.4242	0.3157	0.4267	0.2034	0.3738	0.4855	0.1193	0.0952	0.0991	0.1874	0.0325	0.0703	0.0289	0.0025
R+C	1.4880	1.1333	0.7889	1.1263	0.8021	0.7663	0.5993	0.9399	0.5865	0.4188	0.5614	0.9346	0.3028	0.4959	0.3827	0.7154	0.3387	0.4387	0.1914	0.7230
R-C	-1.0795	-0.4879	-0.2726	0.0093	-0.0011	-0.0681	-0.2491	0.3084	-0.2669	0.0121	-0.1863	-0.0364	0.0643	0.3055	0.1845	0.3405	0.2737	0.2981	0.1336	0.7180

Table 4.9: Importance of agile manufacturing impediments

Impediments	**PCC**	**DCM**	**IIV**	**OCO**	**LCC**	**DCC**	**LHR**	**LRR**	**SBM**	**III**	**LFR**	**RVM**	**ICF**	**ICC**	**LTP**	**HTT**	**IMF**	**IIH**	**ISC**	**ISP**
R + C	1.4880	1.1333	1.1263	0.9399	0.9346	0.8021	0.7889	0.7663	0.7230	0.7154	0.5993	0.5865	0.5614	0.4959	0.4387	0.4188	0.3827	0.3387	0.3028	0.1914
Ranking	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Table 4.10: Cause and effect groups of agile manufacturing impediments

Impediments	ISP	HTT	LRR	ICC	IIH	IMF	LTP	ISC	ICF	III	OCO	LCC	RVM	DCC	LFR	LHR	SBM	IIV	DCM	PCC
R - C	0.7180	0.3405	0.3084	0.3055	0.2981	0.2737	0.1845	0.1336	0.0643	0.0121	0.0093	-0.0011	-0.0364	-0.0681	-0.1863	-0.2491	-0.2669	-0.2726	-0.4879	-1.0795
Grouping	Cause group of agile manufacturing impediments											Effect group of agile manufacturing impediments								

Table 4.11: Reduced total relationship matrix

	PCC	**DCM**	**LHR**	**IIV**	**DCC**	**LRR**	**LFR**	**OCO**	**RVM**	**HTT**	**ICF**	**LCC**	**ISC**	**ICC**	**IMF**	**III**	**IIH**	**LTP**	**ISP**	**SBM**
PCC	0.0000	0.0578	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0535	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DCM	0.0520	0.0000	0.0394	0.0000	0.0000	0.0000	0.0000	0.0000	0.0555	0.0240	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0208	0.0000	0.0000
LHR	0.0653	0.0000	0.0000	0.0438	0.0000	0.0000	0.0000	0.0378	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

	PCC	DCM	LHR	IIV	DCC	LRR	LFR	OCO	RVM	HTT	ICF	LCC	ISC	ICC	IMF	III	IIH	LTP	ISP	SBM
IIV	0.0731	0.0036	0.0000	0.0705	0.0326	0.0450	0.0000	0.0290	0.0000	0.0000	0.0663	0.0361	0.0000	0.0000	0.0000	0.0107	0.0000	0.0000	0.0000	0.0000
DCC	0.0403	0.0000	0.0274	0.0311	0.0437	0.0105	0.0000	0.0000	0.0596	0.0000	0.0000	0.0000	0.0000	0.0000	0.0245	0.0000	0.0000	0.0000	0.0000	0.0000
LRR	0.0255	0.0617	0.0000	0.0000	0.0000	0.0000	0.0569	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0063	0.0000	0.0540	0.0000	0.0000	0.0000	0.0000
LFR	0.0530	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0368	0.0000	0.0000	0.0044	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
OCO	0.0653	0.0555	0.0293	0.0318	0.0129	0.0561	0.0459	0.0000	0.0333	0.0000	0.0434	0.0463	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RVM	0.0582	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0366	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HTT	0.0000	0.0269	0.0000	0.0000	0.0277	0.0000	0.0000	0.0000	0.0000	0.0000	0.0249	0.0000	0.0000	0.0063	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ICF	0.0129	0.0000	0.0000	0.0000	0.0549	0.0000	0.0000	0.0000	0.0434	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LCC	0.0261	0.0480	0.0288	0.0467	0.0000	0.0153	0.0444	0.0451	0.0000	0.0000	0.0000	0.0000	0.0000	0.0056	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISC	0.0267	0.0107	0.0000	0.0000	0.0000	0.0000	0.0248	0.0241	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ICC	0.0673	0.0523	0.0607	0.0000	0.0000	0.0391	0.0000	0.0000	0.0000	0.0000	0.0000	0.0448	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
IMF	0.0643	0.0000	0.0214	0.0000	0.0250	0.0000	0.0228	0.0000	0.0000	0.0000	0.0000	0.0000	0.0212	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
III	0.0640	0.0460	0.0445	0.0488	0.0319	0.0000	0.0206	0.0000	0.0482	0.0000	0.0453	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
IIH	0.0654	0.0000	0.0554	0.0133	0.0000	0.0560	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LTP	0.0642	0.0674	0.0000	0.0282	0.0000	0.0000	0.0000	0.0000	0.0000	0.0258	0.0000	0.0459	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ISP	0.0598	0.0409	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SBM	0.0688	0.0597	0.0018	0.0411	0.0000	0.0327	0.0347	0.0302	0.0000	0.0000	0.0000	0.0638	0.0265	0.0000	0.0210	0.0411	0.0078	0.0000	0.0063	0.0000

Table 4.12: IIV's strength of influencing on and influenced by other agile manufacturing impediments

Criteria	Strength of influencing	Criteria	Strength of influenced
PCC	0.0731	IIV	0.0705
IIV	0.0705	III	0.0488
ICF	0.0663	LCC	0.0467
LRR	0.045	LHR	0.0438
LCC	0.0361	SBM	0.0411
DCC	0.0326	OCO	0.0318
OCO	0.029	DCC	0.0311
III	0.0107	LTP	0.0282
DCM	0.0036	IIH	0.0133

Table 4.13: List of agile manufacturing impediments influencing each impediment

AM impediments	AM impediments influencing the impediments	Prominent AM impediments influencing the impediments
PCC	DCM, LCC	DCM, LCC
DCM	RVM, PCC, LHR, HTT, LTP	RVM, PCC, LHR
LHR	PCC, IIV, OCO	PCC, IIV
IIV	PCC, IIV, ICF, LRR, LCC,DCC, OCO, III, DCM	PCC, IIV, ICF, LRR, LCC
DCC	RVM, DCC, PCC, IIV, LHR, IMF, LRR	RVM, DCC, PCC, IIV
LRR	DCM, LFR, III, PCC, ICC	DCM, LFR
LFR	PCC, HTT, ISC	PCC, HTT
OCO	PCC, LRR, DCM, LCC, LFR, ICF, RVM, IIV,LHR, DCC	PCC, LRR, DCM, LCC, LFR, ICF
RVM	PCC, ICF	PCC
HTT	DCC, DCM, ICF, ICC	DCM, DCC, ICF
ICF	DCC, RVM, PCC	DCC, RVM
LCC	DCM, IIV, OCO, LFR, LHR, PCC, LRR, ICC	DCM, IIV, OCO, LFR
ISC	PCC, LFR, OCO, DCM	PCC, LFR, OCO
ICC	PCC, LHR, DCM, LCC, LRR	PCC, LHR, DCM
IMF	PCC, DCC, LFR, LHR, ISC	PCC, DCC, LFR
III	PCC, IIV, RVM, DCM, ICF, LHR, DCC, LFR	PCC, IIV, RVM, DCM, ICF
IIH	PCC, LRR, LHR, IIV	PCC, LHR, LRR
LTP	DCM, PCC, LCC, IIV, HTT	DCM, PCC, LCC
ISP	PCC, DCM	PCC, DCM
SBM	PCC, LCC, DCM, IIV, III, LFR, LRR, OCO, ISC, IMF, IIH, ISP, LHR	PCC, LCC, DCM, IIV, III, LFR, LRR

Table 4.14: List of agile manufacturing impediments influenced by each impediment

AM impediments	Influenced AMIs	Prominent influenced AMIs
PCC	IIV, SBM, ICC, IIH, OCO, LHR, IMF, LTP, III, ISP, RVM, LFR, DCM, DCC, ISC, LCC, LRR, ICF	IIV, SBM, ICC, IIH, OCO, LHR, IMF, LTP, III, ISP, RVM, LFR
DCM	LTP, LRR, SBM, PCC, OCO, ICC, LCC, III, ISP, HTT, ISC, IIV	LTP, LRR, SBM, PCC, OCO, ICC, LCC
LHR	ICC, IIH, III, DCM, OCO, LCC, DCC, IMF, SBM	ICC, IIH, III, DCM, OCO
IIV	IIV, III, LCC, LHR, SBM, OCO, DCC, LTP, IIH	IIV, III, LCC, LHR, SBM, OCO
DCC	ICF, DCC, IIV, III, HTT, IMF, OCO	ICF, DCC, IIV, III
LRR	OCO, IIH, IIV, ICC, SBM, LCC, DCC	OCO, IIH, IIV, ICC
LFR	LRR, OCO, LCC, SBM, ISC, IMF, III	LRR, OCO, LCC, SBM
OCO	LCC, LHR, SBM, IIV, ISC	LCC, LHR, SBM
RVM	DCC, DCM, III, ICF, OCO	DCC, DCM, III
HTT	LFR, LTP, DCM	LFR, LTP
ICF	IIV, III, OCO, RVM, HTT	IIV, III, OCO
LCC	SBM, PCC, OCO, LTP, ICC, IIV	SBM, PCC, OCO, LTP
ISC	SBM, IMF, LFR	SBM, IMF
ICC	LRR, HTT, LCC	LRR, HTT
IMF	DCC, SBM	DCC
III	LRR, SBM, IIV	LRR, SBM
IIH	SBM	SBM
LTP	DCM	DCM
ISP	SBM	SBM
SBM	NULL	NULL

4.3.3 Results and Discussion

The results obtained by applying the proposed model in an Indian automobile manufacturing company, are discussed under the sections (4.3.3.1, 4.3.3.2 and 4.3.3.3) i.e. ranking of AMIs, classification of AMIs into cause and effect groups and establishment of interactions for each AMI using IRM.

4.3.3.1 Ranking of AMIs

The ranking of AMIs was carried out on the basis of $R+C$ vector to know the importance of the AMIs (Table 4.9). For the case company, Poor Core Competency (PCC) was the most important AMI with the highest $R+C$ value of 1.4880, while Improper Strategic Plan (ISP) was the least important with the lowest of $R+C$ value of 0.1914. The degrees of importance of all AMIs are shown in Table 4.9. A Pareto chart (Figure 4.3) was developed considering the degrees of importance to identify the group of important AMIs. From the Pareto chart, seven AMIs (i.e. Poor Core Competency (PCC), Difficulty in Change Management (DCM), Inadequate Information Visibility (IIV), Operational Constraints (OCO), Lack of Responsiveness in Capturing customer requirements (LCC), Degree of Command and Control hierarchy (DCC) and Lack of Human Resource (LHR)) were identified as important AMIs. These AMIs have significant negative impact on the AM performance.

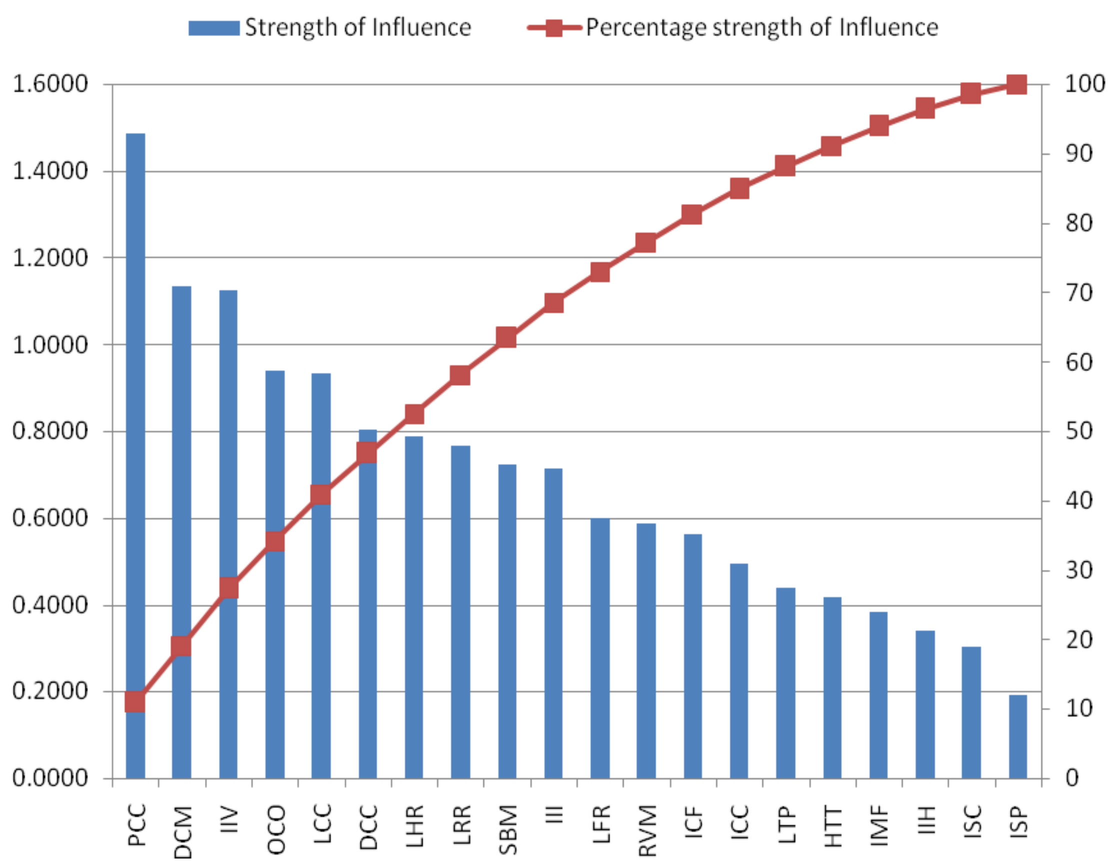

Figure 4.3: PARETO chart to identify group of important AMIs

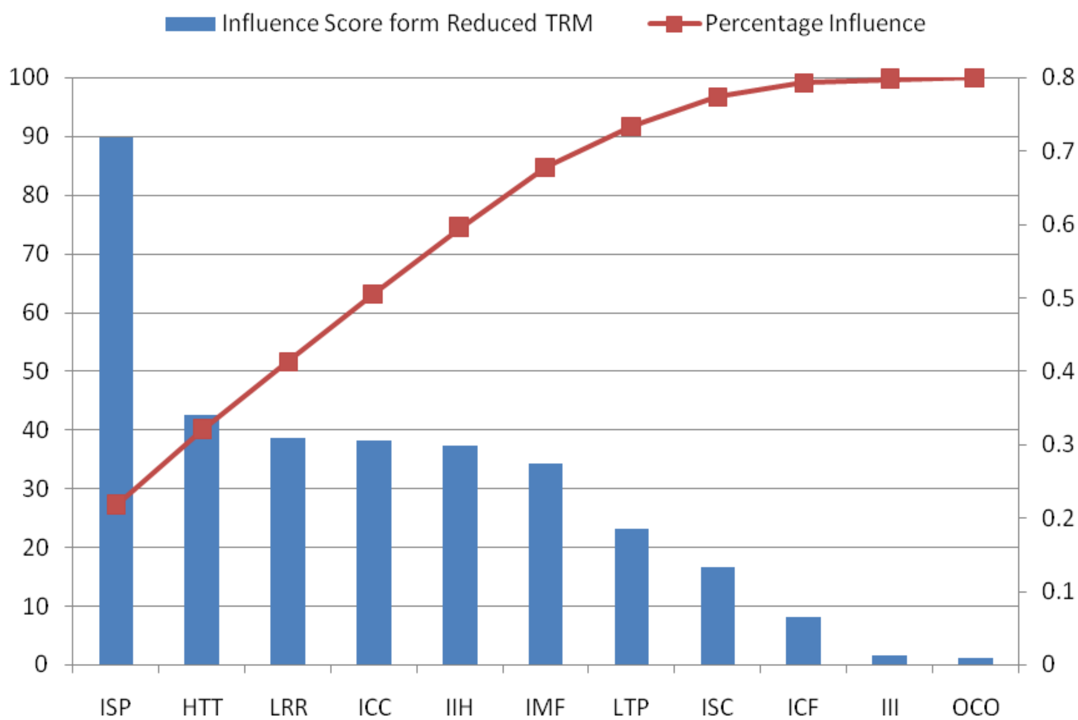

Figure 4.4: PARETO chart to identify group of important agile manufacturing impediments influencing

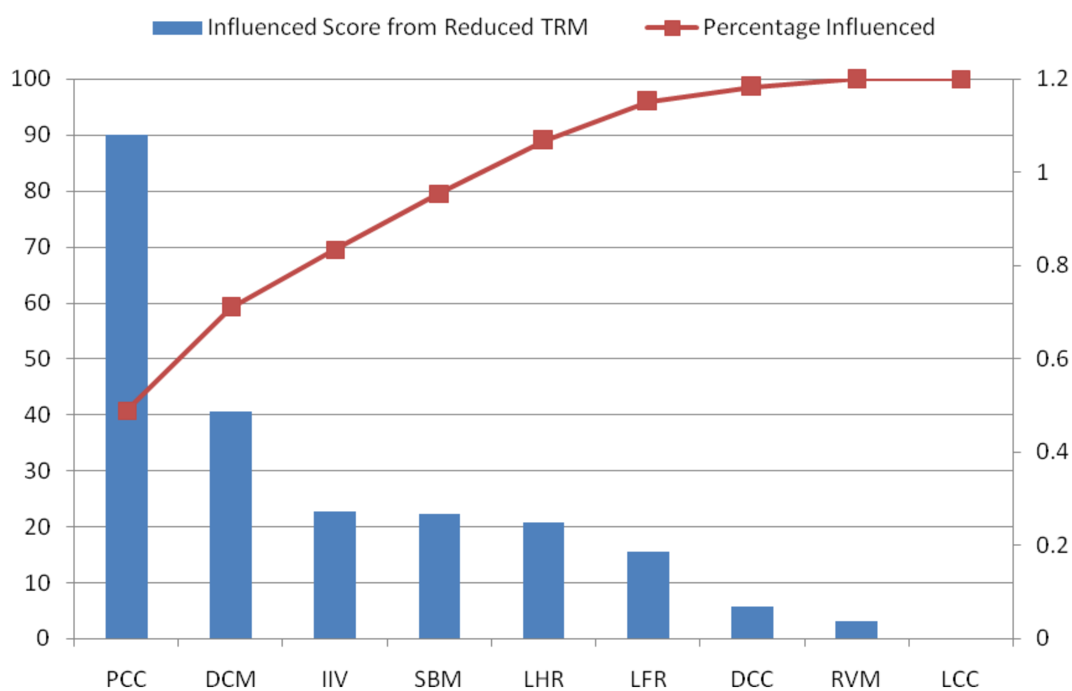

Figure 4.5: PARETO chart to identify group of important agile manufacturing impediments influenced

4.3.3.2 Classification of AMIs into cause and effect groups

The AMIs were divided into cause and effect group on the basis $R-C$ vector (Table 4.9). Eleven AMIs (i.e. ISP, HTT, LRR, ICC, IIH, IMF, LTP, ISC, ICF, III and OCO) were identified under cause group and rest nine AMIs (i.e. LCC, RVM, DCC, LFR, LHR, SBM, IIV, DCM and PCC) were identified under effect group. The most influencing AMI is found out to be improper strategic plan (ISP) with highest $R-C$ value of 0.7180 whereas the most influenced AMI is found out to be Poor Core Competency (PCC) with the lowest $R-C$ value of minus 1.0795. The Pareto charts (see Figure 4.4 and Figure 4.5) are also made on the basis of degree of influencing and degree of influenced for both cause and effect groups respectively to identify the prominent group of AMIs in each group. The prominent AMIs of cause group are Improper Strategic Plan (ISP), Lack of Resource Reconfiguration (LRR), Inefficient Conflicting Management styles (ICC), Inadequate Information Handling (IIH) and Imperfect Market Knowledge (IMF) whereas the prominent AMIs of effect group are Poor Core Competency (PCC), Difficulty in Change Management (DCM), Inadequate Information Visibility (IIV), Supplier Base far from Manufacturer (SBM) and Lack of Human Resource (LHR). Causal diagram (see Figure 4.2) is also made by plotting $R+C$ vector values as abscissas and $R-C$ values as ordinates on a Cartesian plane to show the distribution of AMIs visually.

4.3.3.3 Establishment of interactions for each AMI using IRM

As twenty AMIs have been considered in the case situation, it was difficult to represent the interactions of all AMIs in one Impact Relationship Map (IRM). Therefore, the IRM for each AMI has been developed based on the reduced TRM matrix to visualize its interactions (i.e. influencing and influenced) among other AMIs. Although IRMs' for all the AMIs have been developed, only IRM for "IIV" AMI is shown in the Figure 4.6. Each AMI influences and gets influenced by a number of AMIs and the prominent of such AMIs are obtained from individual Pareto chart. The details are mentioned in Table 4.13 and Table 4.14 respectively.

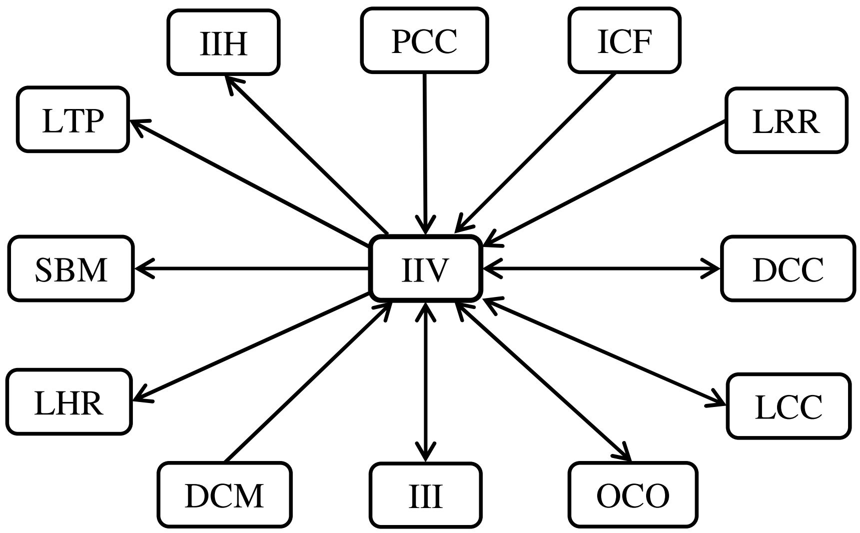

Figure 4.6: Impact relationship map of inadequate information visibility (IIV)

4.4 Addressing Significant Category of AMIs using ISM with FMICMAC

In this study, flexible multi objective decision making approach, ISM is used to study the inter-relationships among recognized significant category of AMIs. In addition to it is more important for the organization to interpret how, and in what way each impediment influences other impediments in a specific environment. The necessary details of ISM integrated with FMICMAC are given in the subsequent subsections and it will also justify its adoption.

4.4.1 Proposed Methodology on Significant Category of Agile Manufacturing Impediments using ISM & FMICMAC

The proposed methodology was developed using Interpretive Structural modelling (ISM) and Fuzzy Matriced Impacts Croises Multiplication Appliqueeaun Classement (FMICMAC) analysis (see Figure 4.7). The step by step procedure of ISM and FMICMAC algorithm is presented in Section 4.4.1.1 and section 4.4.1.2 respectively. Inputs from multiple experts' were taken in binary and fuzzy scale for identified significant categories of AMIs (see Table 4.2). In the first stage, the Structural Self-interaction matrix (SSIM) was developed from the judgments of the team of multiple experts'. The SSIM is then fed into the ISM algorithm coded in MATLAB. The Initial Reachability Matrix (IRM) is developed by converting the SSIM into a binary matrix as per the steps provided in Section 4.4.1.1. The ISM algorithm gives output to draw a conclusion of the hierarchical structure of all the significant category of AMIs by level partitioning. The results obtained from the ISM algorithm will help in understanding the relationship between significant categories of AMIs. However to improve the analysis, ISM is integrated with FMICMAC analysis giving the experts more degree of freedom to express their views. The same team of experts was consulted again to take the inputs for developing the Fuzzy Direct Relationship Matrix (FDRM) of significant category of AMIs. The FDRM data is then again fed to the FMICMAC algorithm coded in MATLAB as per steps discussed in Section 4.4.1.2. The FMICMAC algorithm gives the driving and dependence power of each significant category of AMIs by summing up the rows and columns of the converged matrix. The detail steps of the proposed algorithm are described in the following sections.

4.4.1.1 ISM algorithm

ISM methodology has the ability to draw the order and direction of relationships among impediments/impediments/obstacles of a complex system (Sage, 1977). ISM presents a hierarchical structure that depicts the direct and indirect linkages between the various factors in a system based on priority, precedence and causality over and among each other (Mishra *et. al*., 2014; Kumar and Routroy, 2014; and Routroy and Kumar, 2015). Recently many researchers have used ISM as a quantitative tool in various environments The ISM methodology used in the study is shown in Figure 4.6 and discussed below:

Step 1: Identify the significant category of AMIs through literature review, brainstorming sessions and expert opinions.

Step 2: Form a group of experts (favorably seven to ten) drawn from company and academics with experience and knowledge in the said field.

Step 3: Carry out the thematic content analysis to define the domain of each AMI on the basis of experts remarks obtained from step 1. Consider the irredundant, properly accounted, relevant and significant category of AMIs to develop Structural Self-Interaction Matrix (SSIM).

Step 4: Develop SSIM by drawing contextual relationships among the significant category of AMIs on the basis of experts' opinion. Use four symbols (A: AMI 'j' leads to AMI 'i'; V: AMI 'i' leads to AMI 'j'; X: AMI 'i' leads to AMI 'j' and AMI 'j' leads to AMI 'i' and O: No relationship between AMI 'i' and AMI 'j') for the type of the relation that exists between the Significant category of AMIs ('i' and 'j').

Step 5: Develop the Initial Reachability Matrix (IRM) by converting the SSIM into a binary matrix, substituting V, A, X and O by 1 and 0. The substitution by 1's and

0's are as per the following rules: If the (i, j) entry in the SSIM is V, then the (i, j) entry in the IRM becomes 1 and the (j, i) entry becomes 0. If the (i, j) entry in the SSIM is A, then the (i, j) entry in the IRM becomes 0 and the (j, i) entry becomes 1. If the (i, j) entry in the SSIM is X, then the (i, j) entry in the IRM becomes 1 and the (j, i) entry also becomes 1. If the (i, j) entry in the SSIM is O, then the (i, j) entry in the IRM becomes 0 and the (j, i) entry also becomes 0.

Step 6: Develop the Final Reachability Matrix (FRM) from IRM considering transitivity among the contextual relations of significant category of AMIs. Determine the transitivity in the relationship as follows: if AMI "i" is related to AMI 'j' and AMI 'j' is related to AMI 'k', then AMI 'i' is related to AMI 'k'. Then the (i, k) entry in the FRM becomes 1*. Determine the driving and dependence power of each AMI by taking summation of the elements along the rows and columns of FRM respectively. Rank the significant category of AMIs on the basis of driving and dependence powers.

Step 7: Carry out the level partitioning of significant category of AMIs by developing the reachability and antecedent sets for each AMI on the basis of FRM. The reachability set of an AMI contains the AMI itself and other significant category of AMIs which it may reach. Whereas, the antecedent set of an AMI contains the AMI itself and other significant category of AMIs which may reach it. The Significant category of AMIs for which the reachability and intersection sets are same will occupy the top-level in the ISM hierarchy. Separate out the top-level significant category of AMIs from the initial set of significant category of AMIs and then repeat the process until all the significant categories of AMIs is assigned to a level.

Step 8: From the obtained level partitions, develop a lower triangular matrix or canonical matrix. It is just another form of FRM in which significant category of AMIs are positioned and clustered according to the level of partition. This canonical matrix forms the basis for developing a directed graph called as digraph. If a relationship (directly or indirectly) exists between significant category of AMIs 'i' and significant category of AMIs 'j', this is shown by an arrow (i.e. link) which points from significant category of AMIs 'i' to significant category of AMIs 'j'.

Step 9: Develop the final structural model of significant category of AMIs by eliminating the transitivity links in the diagraph (obtained in the step 8) and considering the level partitions (in step 7) and FRM (in step 6).

Step 10: Review the structural model of significant category of AMIs developed in Step-9 for conceptual accuracy. If it is not conceptually accurate, then go to Step 3.

Step 11: Based on the driving and dependence powers obtained in the step 6, carry out the Fuzzy MICMAC analysis (see Section 4.4.1.2).

4.4.1.2 Fuzzy MICMAC analysis algorithm

Although MICMAC analysis can classify significant category of AMIs, there is a limitation in this process. Since the relationships between Significant category of AMIs are recorded in terms of binary values (either 0 or 1), there is no enough degree of freedom for experts in expressing the strength of relationship between the Significant category of AMIs. To resolve the above issue, FMICMAC analysis should be carried out. The objective of the FMICMAC analysis is to divide the significant category of AMIs into four quadrants namely autonomous, dependent, linkage and driver. The steps mentioned below are to be followed to conduct FMICMAC analysis:

Step 1: In the FRM (see step 6 of the ISM algorithm in the Section 4.4.1.1), replace all the diagonal elements along with the transitive relationships with 0's to obtain a Binary Direct Relationship Matrix (BDRM).

Step 2: Using the same experts' judgments (see step 4 of the ISM algorithm in the Section 4.4.1.1); recollect the relationships between the Significant category of AMIs in the BDRM to obtain fuzzy Direct Relationship Matrix (FDRM).

Step 3: Raise the FDRM's power by fuzzy matrix multiplication (rule: $C = \max_k \{\min (a_{ik}, b_{kj})\}$ where $A = [a_{ik}]$, $B = [b_{kj}]$) till it is converged. Determine the convergence point where the driving and dependence powers of significant category of AMIs are stabilized or cyclic in their variation with certain periodicity.

Step 4: Based on the new driving and dependence powers obtained from the final converged matrix, plot the driver dependence diagram (with dependence power along the X-axis and driving power along the Y-axis) and classify the Significant category of AMIs in to four groups (i.e. autonomous having lower dependence and driver power, dependent having higher dependence and lower driver power, linkage having higher dependence and driver power and independent having lower dependence and higher driving power).

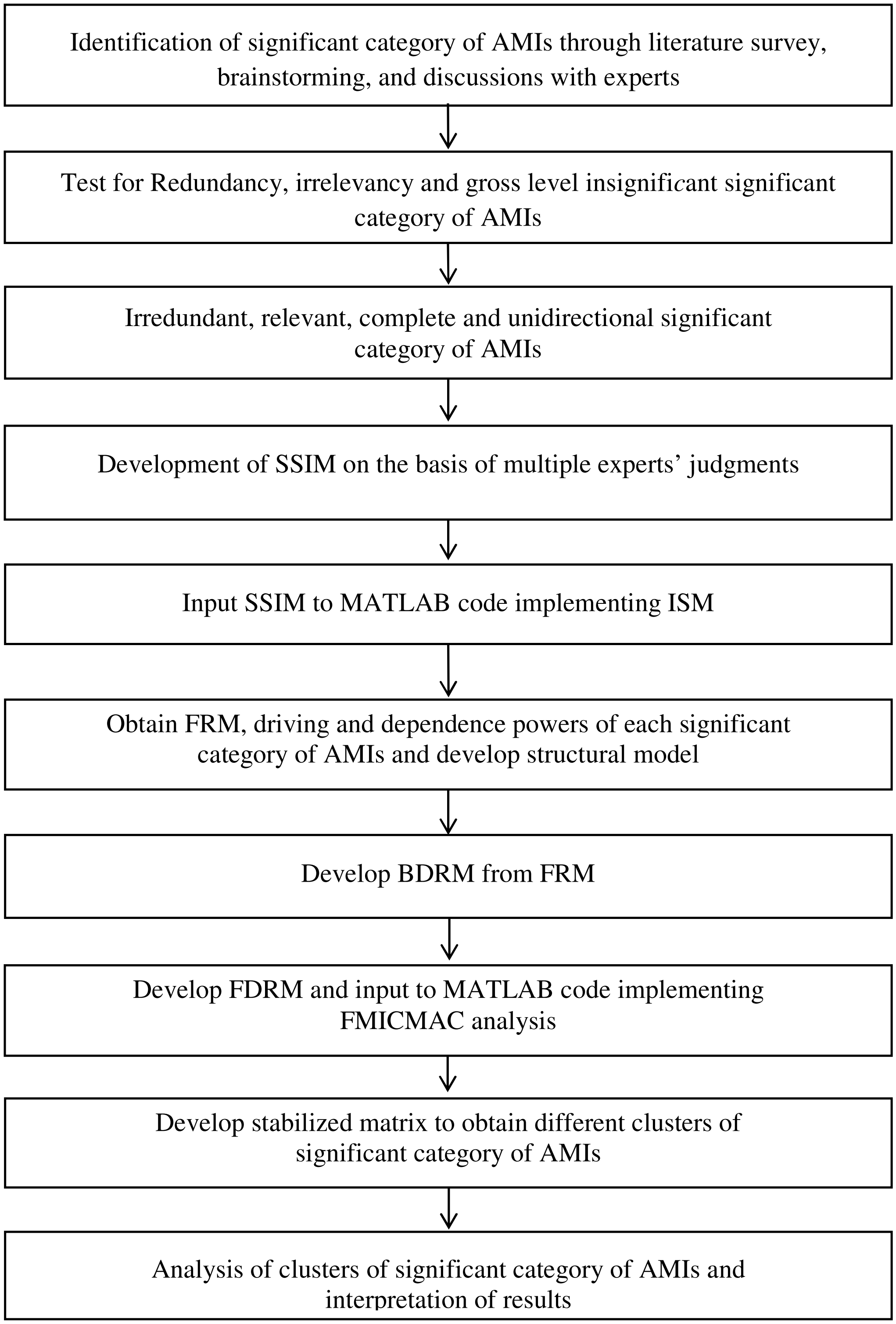

Figure 4.7: Flowchart of the proposed methodology for analysing significant category of AMIs

4.5 Implementing of Proposed Methodology in an Indian Automotive Manufacturing Company

The proposed methodology was applied to an Indian automobile manufacturing company for analyzing the significant category of AMIs. The details regarding case company is discussed in Section 4.3.2. After holding detailed discussions with the top management and the people responsible for implementing AM, some gross to delicate problems were uncovered which are seriously affecting the implementation of AM in the case company. A team of multiple experts (i.e. ten) from the cross functional departments having more than 7-10 years of experience in the case company were formed. A detailed discussion was held with them regarding the related issues with significant categories of AMIs of the case company. There are different aggressive opinions among the experts, when discussed regarding the significant category of AMIs. The above proposed methodology and its objectives were explained to the experts and were asked to give their opinions at two stages. The company experts were motivated with the proposed methodology and agreed to cooperate. The eleven significant category of AMIs as mentioned in previous section were discussed with the team experts to check for relevancy, significance and accountancy. Finally, it was concluded that the eleven significant category of AMIs were significant for the case company to implement AM. The relationship among 11 significant category of AMIs was explored with the help of a structured questionnaire administered to the expert. The questionnaire consists of various questions to collect the qualitative opinions about the relationship between the significant categories of AMIs. For collecting the qualitative opinions, ten experts were asked to choose one among the following four types of relationship (i.e. V, A, X and O) between the significant categories of AMIs (see Step 4 in Section 4.4.1.1) and further analysis was carried out as mentioned in Section 4.4.1.2.

4.6 Results and Discussions

The results obtained after implementation of the proposed methodology is discussed in Sections i.e. Section 4.6.1, Section 4.6.2, and Section 4.6.3 (i.e. level partitioning, development of ISM Model and significant category of AMIs classification). Each section is discussed in detail below.

4.6.1 Level Partitioning

Level partitioning is the basis for constructing ISM model. In the current study, significant categories of AMIs were leveled across five levels in five iterations (see Figure 4.8). LMI is positioned in the level-V and it is having high driving power while IHR and EBE at IV level. The bottom most level's Significant category of AMIs represent the impediments that can be alleviate easily as well as used to lessen the other significant category of AMIs located in the higher levels. The significant category of AMIs: IIM, LMF, IPP, ICR, ISC are positioned in the level-I and have high dependence power (i.e. closer to 11) with different driving powers. The Significant category of AMIs positioned in this level represent the long standing delicate impediments due to which current AM implementation process is clogged up. These Significant categories of AMIs should be treated strategically in order to achieve the excellence in AM implementation. The significant category of AMIs positioned in the other levels can be treated as those which are to be tactically addressed in the AM implementation process.

4.6.2 Development of ISM Model

The diagraph was obtained considering the direct and transitive relationship between significant categories of AMIs. After removing all the transitivity links present from the diagraph, the ISM model was developed.

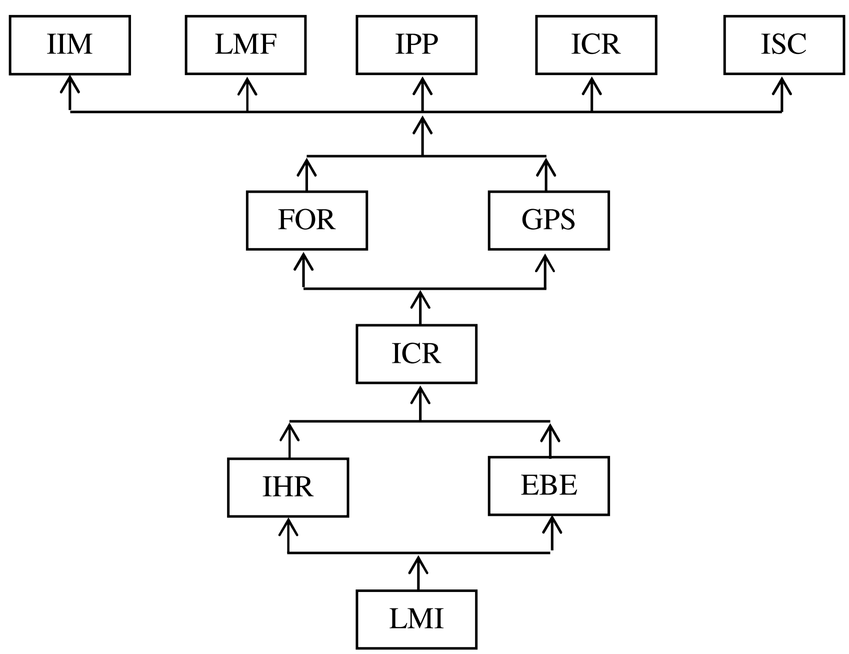

Figure 4.8: ISM model of agile manufacturing impediments

The developed ISM model was shown (see Figure 4.8) and discussed with experts for its acceptability. The experts have agreed on the developed ISM model. In the structural model significant category of AMIs were arranged in the hierarchy as per the levels partitioned (see Section 4.6.1 to know the significance of levels). Thus, the ISM model (see Figure 4.8) developed presents a directional framework for the case company in successfully implementing AM and gives clear mental picture of what experts think about the relationship between significant categories of AMIs and their significance in improving AM implementation process.

4.6.3 Significant Category of AMIs Classification

The classification of significant category of AMIs for the case company was carried out through FMICMAC analysis (see Figure 4.9). It is carried on the basis of driving and dependence powers and all 11 Significant category of AMIs were classified into four clusters (i.e. autonomous, driver, dependent and linkage quadrant) which are discussed below:

Autonomous quadrant (*low driving power, low dependence power*): Those significant categories of AMIs which fall in this quadrant are relatively disconnected from the AM implementation process. But in our study, not a single AMI lies in this quadrant. This signifies that, all the identified significant categories of AMIs are relevant to the case company and need to be monitored.

Driver quadrant (*high driving power, low dependence power*)*:* The Significant category of AMIs i.e. EBE, ICM, IHR and LMI were in driver/independent cluster which means that these four Significant category of AMIs have high influence on rest eight other Significant category of AMIs and these were also placed on bottom side of the developed ISM. These significant categories of AMIs have high driving capacity which means by addressing these significant categories of AMIs other significant categories of AMIs can be attenuated. These are significant categories of AMIs which has to be addressed first. The case company was addressed to focus on these four significant categories of AMIs and level up its strategy to mitigate these identified four significant categories of AMIs as much as possible and feasible.

Dependent quadrant (*low driving power, high dependence power*)*:* The significant category of AMIs i.e. ICR, LMF, GPS, ISC, IIM and IPP were clustered in the dependent quadrant. This signifies that these significant categories of AMIs were mainly dependent on the other significant category of AMIs having the capacity to drive the implementation of AM. The

Significant category of AMIs falling in this cluster represent that these are the impediments which cannot be addressed directly but through other significant category of AMIs.

Linkage quadrant (*high driving power, high dependence power*): Out of 11 Significant category of AMIs chosen, only one AMI i.e. FOR fall in this quadrant. This AMI is having high driving and high dependence power. Typically these can be attributed as unstable because they have feedback effect i.e. they get affected by their own action and difficult to manage. However, this AMI cannot be ignored and have to be closely monitored regarding their status in making decisions.

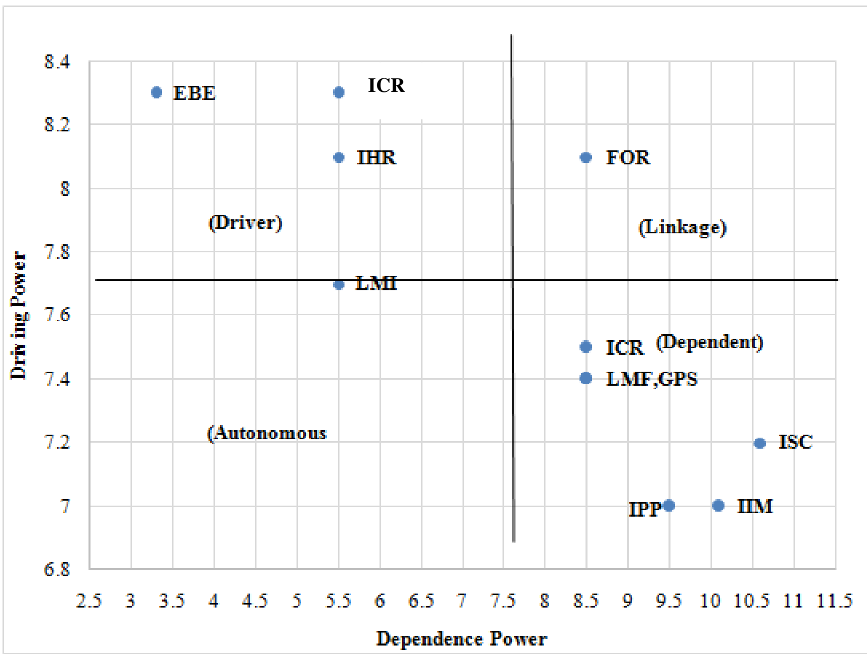

Figure 4.9: FMICMAC driver dependence diagram of significant category of AMIs

4.7 Conclusions

In a manufacturing environment, poor strategic plan and inefficient management affects the results in inadequate core competency and information handling results in inefficient information visibility. It is obvious that focusing more on the causes of a problem, the effects can be managed effectively which in turn enhance the performance of a system. The same concept was applied in the case company using fuzzy DEMATEL to identify the AMIs those were causes for deteriorating the performance of the company. The following relevant observations related to AMIs in the case company were surfaced and recommendations were also made to mitigate the negative impact of significant category of AMIs on AM to enhance its performance.

- Classification of AMIs into cause and effect groups gives the relative ease in controlling/ getting influenced among the AMIs. The case company can easily control AMIs: Improper Strategic Plan (ISP), Lack of Resource Reconfiguration (LRR), Inefficient Conflicting Management styles (ICC), Inadequate Information Handling (IIH) and Imperfect Market Knowledge (IMF) of the cause group (see Figure 4.4). However, ISP, ICC and IIH is the most important as well as easily controllable AMI for the company, whereas the Significant category of AMIs, Poor Core Competency (PCC), Difficulty in Change Management (DCM), Inadequate Information Visibility (IIV), Supplier Base far from Manufacturer (SBM) and Lack of Human Resource (LHR) of the effect group can be easily influenced (see Figure 4.5). But PCC, IIV and LHR are the most important as well as easily influenced AMIs for the company.
- The identified seven important AMIs can be classified into cause and effect groups. The AMI, Operational Constraints (OCO) was identified to be from cause group whereas the Significant category of AMIs, Poor Core Competency (PCC), Difficulty in Change Management (DCM), Inadequate Information Visibility (IIV), Lack of Responsiveness in Capturing customer requirements (LCC), Degree of Command and Control hierarchy (DCC) and Lack of Human Resource (LHR) were identified to be from effect group. Thus, it is obvious that, by only identifying the important AMIs one cannot conclude that on which AMIs; it has to focus as most of the identified important AMIs were found to be from the effect group. So, there is a great necessity of analyzing the AMIs by classifying them into cause and effect group from their $R-C$ value.
- Although it may not be easy to control or get influenced for certain AMIs, nonetheless the company should focus on the important AMIs. The interactions presented using impact relationship map for AMIs help the company to visualize and focus on the important AMIs. High Taxes, Tariffs (HTT) and Imperfect Market Knowledge (IMF) of cause group and Supplier Base far from Manufacturer (SBM) of effect group which are termed as important AMIs do not come under either easily controllable cause group or easily influenced effect group. For ease of presentation, IRM for IIV alone is shown in the Figure 4.6.

The various implications obtained through this proposed approach was explained in specific to the automobile manufacturing company and as well as in general. However, the numerical results obtained are specifically to the case company and these results cannot be generalized for other companies. But, the proposed approach will be quite useful for the managers to find out the most influencing and influenced criteria for a situation by setting the environment according to the requirement. On the basis of the obtained results, one can give a judgement on which criteria the specific company should put his focus.

The second proposed methodology is generic in nature and has the capacity to capture multiple experts' judgment for the analysis of significant category of AMIs in a specific manufacturing environment. For validating the effectiveness, the second proposed methodology is applied to a case company and certain important conclusions were drawn. The Lack of Management Involvement (LMI) was drawn as the most influencing significant category of AMI from the ISM model whereas from FMICMAC analysis, the External Business Environment (EBE), Ineffective Customer Relationship (ICR) and Improper Human Resource Management (IHR) along with LMI were found in driver quadrant (i.e. high driving and low dependence power). By taking both the ISM and FMICMAC model simultaneously LMI, IHR, EBE and ICR were found to be the strongest root cause for other significant category of AMIs. The Inefficient Information Management (IIM), Lack of Manufacturing Flexibility (LMF), Ineffective Production Planning (IPP), Ineffective Customer Relationship (ICR) and Ineffective Supply Chain (ISC) are the prerequisite for the implementation of AM and can be handled by the improvement of the significant category of AMIs in the lower level of ISM model or the significant category of AMIs which lies on the driver quadrant of the FMICMAC model. The case company was delighted with the results obtained from this study. However, the obtained results of the study are specifically to the case company and these results cannot be generalized for other companies. Moreover, the current study may be used as a basis to investigate more details regarding agile manufacturing in general and agile manufacturing impediments in specific.

CHAPTER 5

Measurement of Manufacturing Agility

5.1 Introduction

Constant change and ever increasing turbulence in today's business environment has exerted tremendous pressure on manufacturing organizations to adopt agile manufacturing strategy as a means to sustain and flourish, and gain competitive advantage. Such turbulence and uncertainty is the primary reason for degeneration in the manufacturing industry (Small and Downey, 1996). Hayes and Wheelwright (1985) argued that the benchmark for companies operating in these demanding and difficult environments is the establishment of global competitive advantage through the use of superior manufacturing capabilities and dexterity. The primary requirements for organizations to survive in such harsh operational environments are flexibility and speed of response to market changes as well as the ability to innovate in both product and processes (Smithson and Hirscheim, 1998). Agile manufacturing emerged as the paradigm to survive in such environments possessing characteristics like flexibility and increased response speed. In order to continually operate using agile manufacturing, under difficult operating environments, it is important to measure and improve the agility of the corresponding manufacturing systems. AMEs are defined as the characteristics that have the capability to enable or enhance the present level of agility in the manufacturing system. Although many methods for measuring manufacturing agility have been proposed and reported in literature, pertinent research gaps exist (see Section 5.3.1). Therefore, a methodology for measuring agility by capturing multiple experts' judgement with respect to the AMEs is proposed.

Section 5.2 identifies the AMEs from exhaustive literature review. Section 5.3 proposes the methodology for measuring manufacturing agility. In Section 5.3.3, the methodology was applied to an Indian manufacturing organization. Section 5.3.4 documents the result of the study and Section 5.4 mentions the managerial implications. Section 5.5 provides the concluding remarks and some pointers for future research.

5.2 Identification of Agile Manufacturing Enablers (AMEs)

An exhaustive literature review was conducted to obtain the AMEs proposed by various authors. The various AMEs obtained from the literature review were grouped into eleven categories. AMEs conveying the same meaning or pointing to a common theme have been grouped under one category. For example, supplier development, supplier involvement and supplier selection and evaluation depict the relationship of the local firm with their suppliers. Therefore, they have been aggregated under "Supplier Relationship Management". The AMEs identified (see Table 5.1) from the literature review are: Adaptability (ADP), Product and Process Automation (PPA), Supply Chain Integration (SCI), Core Competency (CCT), Supply Chain Key Partner's Alacrity (SCP), Devolution of Authority (DOA), Information Visibility and Transparency (IVT), Manufacturing Management (MFM), Customer Relationship Management (CRM), Supplier Relationship Management (SRM), and Human Resource Management (HRM). A brief description of each AME is given in Table 5.1.

Table 5.1: Proposed AMEs and their corresponding terms identified from literature

S.No.	AME	Relevant terms identified from literature
1	Adaptability	Technology adoption (Lee and Lau, 1999; Yusuf *et al.*, 1999; Zhang and Sharifi, 2000; Ramasesh *et al.*, 2001; Wang and Lo, 2003; Vazquez-Bustelo *et al.*, 2007; Vinodh and Devadasan, 2011; and Beck, 2012); Responsiveness to business environments (Kidd, 1995Sharifi and Zhang, 1999; Zhang and Sharifi, 2000; Jackson and Johansson, 2003; and Ramesh and Devadasan, 2007); Responsiveness to customer requirement (Sharifi and Zhang, 1999; Zhang and Sharifi, 2000; Wang and Lo, 2003; Ramesh and Devadasan, 2007; and Sherehiy *et al.*, 2007); Changes in social factors (Sharifi and Zhang, 1999; Zhang and Sharifi, 2000; and Sherehiy *et al.*, 2007); Changes in economic factors (Sharifi and Zhang, 1999); Responsiveness to environmental factors (Sharifi and Zhang, 1999); Design flexibility (Abdel-Malek *et al.*, 2000); Creation of fast response teams (Yusuf *et al.*, 1999); Infrastructure re-configurability (Kidd, 1995; Zhang *et al.*, 2002; Jackson and Johansson, 2003; and Lim and Zhang, 2004) and Operations flexibility (Sharifi and Zhang, 1999; Ramasesh *et al.*, 2001; Jackson and Johansson, 2003; Sherehiy *et al.*, 2007; Erande and Verma, 2008; and Flumerfelt *et al.*, 2012).
2	Product and Process Automation	Automated product design analysis (Ramesh and Devadasan, 2007; Vazquez-Bustelo *et al.*, 2007; Vinodh *et al.*, 2009; Vinodh *et al.*, 2010; and Vinodh and Kuttalingam, 2011); Automated product manufacturing analysis (Vazquez-Bustelo *et al.*, 2007; Vinodh *et al.*, 2009; and Vinodh and Kuttalingam, 2011); Rapid prototyping (Vazquez-Bustelo *et al.*, 2007; Vinodh and Chintha, 2011; Beck, 2012;and Vinodh *et al.*, 2013); Computer aided process planning (Vazquez-Bustelo *et al.*, 2007); Computer aided maintenance management (Gunasekaran, 1998), Computer aided quality control and inspection (Gunasekaran, 1998).

S.No.	AME	Relevant terms identified from literature
3	Supply Chain Integration	Internal relationship management (Youssef, 1992); Integrated logistics (Samaranayake *et al*., 2011); Profit and risk sharing mechanisms (Goldman *et al*., 1995); Integrated procurement systems (Vazquez-Bustelo *et al*., 2007) and Virtual enterprise creation (Kidd, 1995; Lee and Lau, 1999; Vinodh and Chintha, 2011; and Vinodh *et al*., 2013).
4	Core Competency	Quality (Sharifi and Zhang, 1999; Yusuf *et al*., 1999; Sherehiy *et al*., 2007; and Ramesh and Devadasan, 2007); Product variety and configuration (Sharifi and Zhang, 1999; Ramasesh *et al*., 2001; and Sherehiy *et al*., 2007); Process robustness (Kidd, 1995; and Flumerfelt *et al*., 2012); Multi skilled workforce (Vazquez-Bustelo *et al*., 2007); Workforce attitude (Sharifi and Zhang, 1999) and Research and Development (Gunasekaran, 1998).
5	Supply Chain Key Partner's Alacrity	Market share expansion (Goldman *et al*., 1995); Niche market growth (Sharifi and Zhang, 1999); New market penetration (Ramasesh *et al*., 2001); Leadership aspirations (Pandya *et al*., 1997); World class excellence strategies (Giffi *et al*., 1990) and Top management support (Vazquez-Bustelo *et al*., 2007).
6	Devolution of Authority	Organizational structure (Ramesh and Devadasan, 2007) and Cross functional teams (Vazquez-Bustelo *et al*., 2007).
7	Information Visibility and Transparency	Information accuracy (Gunasekaran, 1998); Information update (Gunasekaran, 1998) and System integration (Yusuf *et al*., 1999).
8	Manufacturing Management	Production methodology (Ramesh and Devadasan, 2007); Manufacturing planning and control systems (Lim and Zhang, 2004; Leitao and Restivo, 2006; and Ramesh and Devadasan, 2007); Manufacturing strategy (Vinodh and Devadasan, 2011); Concurrent Engineering (Vazquez-Bustelo *et al*., 2007; Vinodh and Chintha, 2011; and Vinodh *et al*., 2013); Product life cycle management (Lyu, 1999; Sharifi and Zhang, 1999; Ramesh and Devadasan, 2007; and Beck, 2012).
9	Customer Relationship Management	Customer care (Wang and Lo, 2003); Delivery lead time (Sharifi and Zhang, 1999) and Customer satisfaction and delight (Jackson and Johansson, 2003; and Erande and Verma, 2008).
10	Supplier Relationship Management	Supplier development (Gunasekaran, 1998); Supplier involvement (Gunasekaran, 1998) and Supplier selection and evaluation (Hasan *et al*., 2008).
11	Human Resource Management	Employee training and education (Yusuf *et al*., 1999; and Vazquez-Bustelo *et al*., 2007); Employee rewards (Vazquez-Bustelo *et al*., 2007); Employee involvement and empowerment (Ramesh and Devadasan, 2007; Vazquez-Bustelo *et al*., 2007) and organizational learning (Lee and Lau, 1999; Flumerfelt *et al*., 2012).

Adaptability (*ADP*): It refers to the readiness and willingness of the organization to adopt new methods of operating the manufacturing system and also continually change in response to the ever changing environments.

Product and process automation (*PPA*): It describes the various technologies that might be used to automate the different functions that are routinely carried out by the manufacturing system. Adoption of such automation makes the system faster and programmable, thereby contributes to agile behaviour.

Supply chain integration (*SCI*): It refers to all supply chain partners' working towards a common supply chain goal instead of individual goals. This increases overall supply chain performance which translates to profit for all the supply chain members. Supply chain integration includes both upstream and downstream integration.

Core competency (*CCT*): A core competency is not what an organization does well but a combination of capabilities that are unique, durable and extensive (Routroy, 2009). In order to be agile, it is necessary for firms to concentrate primarily on their core competencies and outsource or eliminate other activities.

Supply chain key partner's alacrity (*SCP*): It refers to the degree of readiness/alertness exhibited by the supply chain partners in response to the business environments. SCP is an important enabler because the supply chain partners should be ready to respond to various changes and hence the parts/components/services can be procured in the shortest possible time.

Devolution of authority (*DOA*): It refers to the process of delegating authority to the other competent members of the organization. It also promotes independent decision making at each level of hierarchy, which translates to quicker decision making.

Information visibility and transparency (*IVT*): It refers to the seamless and real-time availability of accurate information across all levels of the organization. Information is critical to an AM environment in order to analyse the behaviour of the market and the customers' preferences.

Manufacturing management (*MFM*): It is related to transformation process which is core to any manufacturing organization. It includes the set of tools and strategies that provide the foundation for effective manufacturing.

Customer relationship management (*CRM*): It refers to the practices employed by the organization to enhance their relationship with the customers so as to serve them better. It needs understanding, analysing and managing customer expectations and complaints effectively.

Supplier relationship management (*SRM*): It involves close relationships with the suppliers in order to understand and analyse their shortcomings with aim to work together to resolve these shortcomings so that the supplier is able to deliver the right products at the right time which will in turn enhance the agility.

Human resource management (*HRM*): It includes activities and efforts undertaken by the manufacturing organization to engage, motivate and retain their employees which in turn reduces attrition. It positively influences the attitude of the workforce thereby leading to increased productivity and performance.

5.3 Proposed Methodology for Measuring Manufacturing Agility

In order to measure manufacturing agility, a methodology integrating the fuzzy synthetic extent of the weights of AMEs and the average fuzzy performance ratings of the AMEs to develop a Fuzzy Agile Manufacturing Index (FAMI) is proposed. Section 5.3.1 mentions the various models available in literature and proposes the research questions. Section 5.3.2 details the step-by-step methodology for calculating the FAMI.

5.3.1 Methods of Measuring Agility

Various methods of measuring agility have been reported in literature. Lin *et al*. (2006a) proposed and computed a fuzzy agility index by providing the weighted average of the fuzzy ratings. Subsequently, Lin *et al*. (2006b), extended his work on the fuzzy agility index and developed a more comprehensive measure namely, the absolute agility index. This index is helpful in determining the agility of the enterprise as well as its supply chain. It also provides a high degree of flexibility to the decision makers. But, the model was susceptible to high degree of bias from a single decision maker. Jain *et al*. (2008a) employed fuzzy intelligent agents to emulate human decision making and to make decisions with unreliable and incomplete data. They introduced a concept called dynamic agility level index to measure the agility. As before, the model suffers from respondent bias and since supply chain environments continually vary, the membership functions for the fuzzy sets should be continuously revised. Jain *et al*. (2008b) proposed another method using the concept of fuzzy association rules mining to determine the rules for measuring agility. This method provided only the rules for measuring agility but not a measure for agility. Also, this method was based on intricate mathematical fundamentals which may be difficult for the managers to follow. Li *et al*. (2009) developed an instrument for measuring agility based on the information received from literature, expert surveys and judgements. This instrument was also tested and validated but the generalizability of the results needs to be statistically proven. Charles *et al.* (2010) provided an agility score based on certain metrics which include the Key Performance Indicator's (KPIs) of the system under consideration. The contents of this approach were built on strong theoretical fundamentals and utilized symbolic modelling. This method was easy to follow and thereby useful for managers in the industry. But, this approach has been tested specifically on humanitarian aid supply chains and so, their generalizability needs to be validated empirically. Vinodh and Prasanna (2011) developed a multi grade fuzzy approach for measuring agility and proposed agility index as a measure to measure the agility. In this method, the agility index not only indicated the level of agility in the organization but also identified the areas of weakness where improvement is required. Yauch (2011) proposed 'Agility Performance Metric' as a measure of agility. In his approach, the methodology for assessing agility was based on strong theoretical foundations and could easily be applied to various levels in the organization with slight modification. But, statistical validation is pending. Vinodh *et al.* (2013) proposed a method for measuring agility, taking an example of a supply chain. Their method is easy to follow and could be applied to industries. But, this model suffers from respondent bias and it has been applied to only one case organization. Khalili-Damghani and Tavana (2013) proposed a metric namely 'Efficiency of Agility' which was developed using 'Fuzzy Data Envelopment Analysis'. In this method, the amount of computation was significantly reduced and the optimal solution is arrived at easily. But this method was also based on intricate mathematical concepts which the managers in organization might find difficult to follow. Considering the research in the field of measuring agility, two pertinent questions emerge:

- When providing judgement regarding the weights of the enablers, shouldn't the enablers be mutually compared to provide more information regarding their importance? Also, previous studies do not evaluate the consistency of these ratings?
- Previous studies do not provide information regarding the evolution of agility in the enterprise. How was the agility of the enterprise in the past? How it is in the present? How it will be in the future?

5.3.2 Methodology for Measuring Agility

A methodology is proposed for measuring agility of the manufacturing system to answer these two questions posed in the previous section. The proposed methodology combines the fuzzy Analytic Hierarchy Process (AHP) for determining the fuzzy synthetic extents (FSEs) of the weights of the AMEs and the triangular fuzzy numbers (TFNs) for capturing the average performance ratings of AMEs. The performance of the AMEs is judged at three intervals of time which are represented as past performance, present performance and future expectation. The fuzzy synthetic extent of the weights of the AMEs and the average fuzzy performance ratings of the AMEs at each interval of time are combined to determine the Fuzzy Agile Manufacturing Index (FAMI) for the respective time period. Then the Euclidean distance to the nearest predetermined agility level is calculated to determine the performance of the organization along the agile dimension at the specified intervals of time. The details of the proposed six-step methodology are mentioned below and the flowchart is shown in Figure 5.1.

Step 1 *Formation of cross functional team* (*CFT*)

The CFT should consist of various experts drawn from various departments with adequate experience in the organization.

Step 2 *Identification of relevant AMEs*

Identify the list of AMEs through literature review, brainstorming sessions and expert opinions. Check the relevancy of each AME to the specific manufacturing environment to form a set of relevant AMEs.

Step 3 *Determination of fuzzy synthetic extent* (*FSE*) *of each AMEs weight*

The fuzzy AHP method is employed to determine the FSE of each AMEs weight. The FSE in terms of TFN for enabler '*i*' is denoted by W_i. The detailed calculation of FSEs is mentioned below:

Step 3.1 *Construct pair-wise comparison matrices of AMEs*

The pair-wise comparison matrices from each expert are constructed by capturing the importance of one AME over other AMEs. These pair-wise comparisons are carried out on a 1-10 scale (Saaty, 1980) (see Table 5.2).

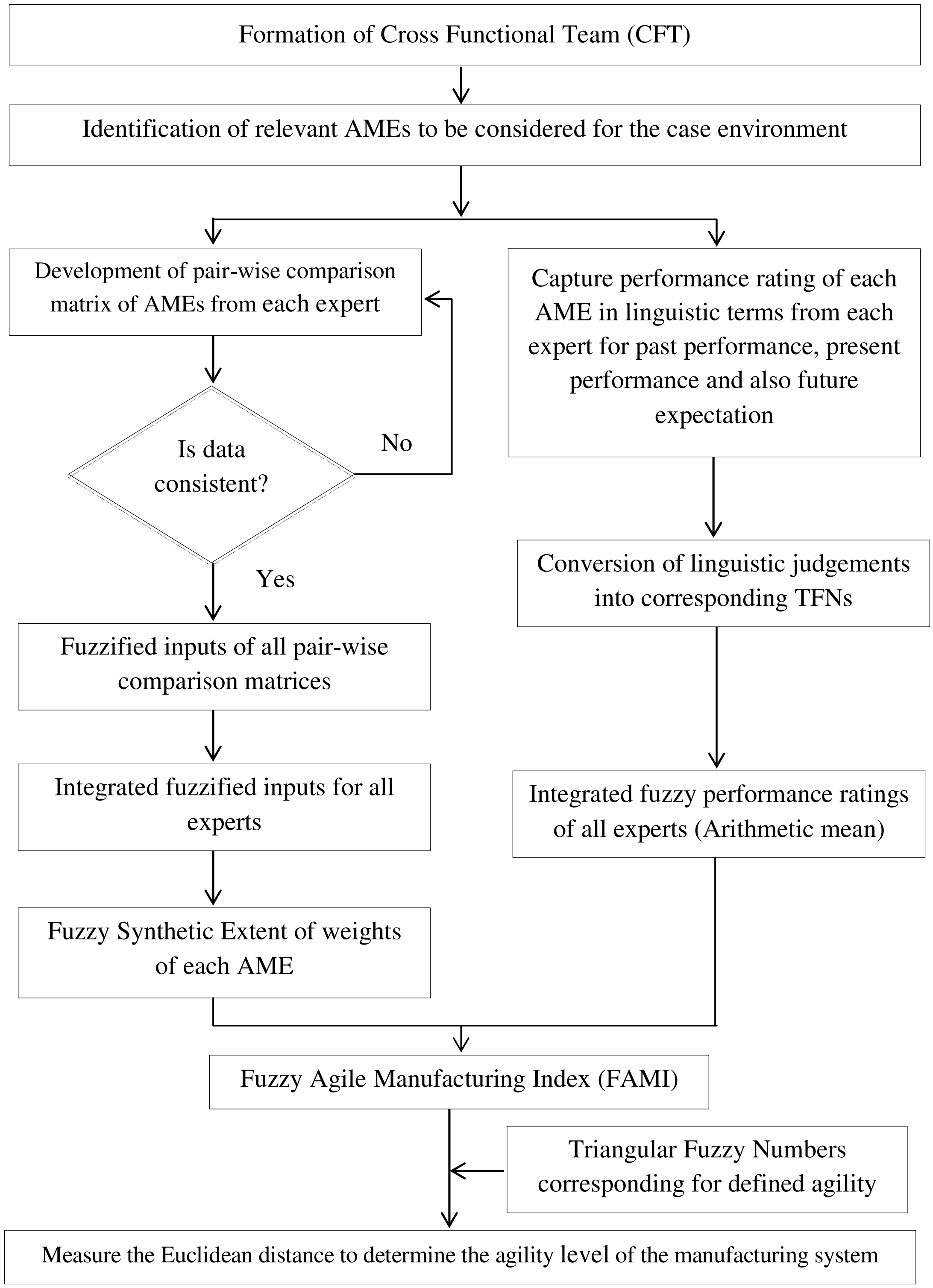

Figure 5.1: Proposed methodology for measuring manufacturing agility

Table 5.2: Scale for pair-wise comparisons (Saaty, 1980)

Importance measure	Definition
1	Equally important
2	Equally to moderately more important
3	Moderately more important
4	Moderate to strongly more important
5	Strongly more important
6	Strong to very strongly more important
7	Very strongly more important
8	Very to extremely strongly more important
9	Extremely more important

Step 3.2 *Check the consistency of pair-wise comparison matrices*

The procedure for computing the Consistency Index (CI) is as follows: Each column of numbers of the pair-wise comparison matrices is normalized by dividing each entry by the sum of the column wise entries. Then the average of the entries across each row is determined. This forms the principal vector (PV). The principal eigenvalue λ_{max} is the aggregate sum of the product of each element of the principal vector and the corresponding column total. Consistency index (CI) can then be calculated as

$$CI = \frac{\lambda_{max} - N}{N - 1}$$

where 'N' is the number of AMEs. Similarly, consistent ratio (CR) is also calculated as

$$CR = \frac{CI}{RI}$$

where RI is the random consistency index corresponding to 'N' (see Table 5.3). If the consistency ratio is less than or equal to 10%, then the judgements are considered to be consistent. If not, the experts have to improve their judgements in such a way that $CR \leq 10\%$.

Table 5.3: Random index values (Saaty, 2000)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Step 3.3 *Fuzzify the pair-wise comparison matrices of each expert (Lee, 2009)*

The individual pair-wise comparison matrix from each expert is fuzzified by replacing the elemental values with the corresponding TFNs (see Table 5.4). The TFNs corresponding to the comparison of enabler '*i*' with enabler '*j*' for the expert '*t*' is denoted as (P_{ijt}, Q_{ijt}, R_{ijt}).

Table 5.4: Membership functions of the fuzzy numbers (Lee, 2009)

Crisp judgement	Triangular fuzzy number
1	(1,1,2)
2	(x-1, x, x+1) for x = 2,3,…,8
9	(8,9,9)
1/1	(2^{-1},1^{-1},1^{-1})
1/x	[$(x+1)^{-1}$, x^{-1}, $(x-1)^{-1}$] for x = 2,3,…,8
1/9	(9^{-1}, 9^{-1}, 8^{-1})

Note: when an enabler '*i'* is compared with itself, although the crisp judgement is 1, the TFN corresponding to this judgement will be (1,1,1)

Step 3.4 *Integrate the fuzzified pair-wise comparison matrices*

The integration of the individual fuzzified pair-wise comparison matrices are performed by means of the geometric mean method and the triangular fuzzy numbers corresponding to the integrated matrix are denoted as (a_{ij}, b_{ij}, c_{ij}). They are calculated according to the expressions provided below (Lee *et al*., 2009b):

$$a_{ij} = \left\{ \prod_{t=1}^{s} P_{ijt} \right\}^{1/s} \quad \forall i, j = 1, 2, \ldots, n$$

$$b_{ij} = \left\{ \prod_{t=1}^{s} Q_{ijt} \right\}^{1/s} \quad \forall i, j = 1, 2, \ldots, n$$

$$c_{ij} = \left\{ \prod_{t=1}^{s} R_{ijt} \right\}^{1/s} \quad \forall i, j = 1, 2, \ldots, n$$

where '*s*' denotes the number of experts participating in providing the judgements.

Step 3.5 *Determine the FSE of AMEs*

FSE (Chang, 1996; Lee, 2009; Lee *et al*., 2009a, b) of weight of AME 'i' is denoted as W_i and is calculated as: (where m_i^-, m_i, m_i^+ indicate the vertices of the triangular fuzzy number)

$$W_i = \left(m_i^-, m_i, m_i^+ \right)$$

$$= \left\{ \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij}}, \frac{\sum_{j=1}^{n} b_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} b_{ij}}, \frac{\sum_{j=1}^{n} c_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}} \right\} \forall i = 1,2,\ldots,n$$

Step 4 *Determination of average fuzzy performance rating of each AME*

The average fuzzy performance rating of each AME is determined based on the expert judgement. The average performance rating is calculated across three time horizons (past, present and future).The average fuzzy performance rating expressed in terms of TFN for enabler '*i*' is denoted as R_i. The procedure for finding the average fuzzy performance rating of AMEs is mentioned below:

Step 4.1 *Capture the expert judgement on the performance rating of each AME*

The experts are asked to judge the performance of the AMEs in the past, in the present and also the expectations for the future in terms of linguistic expressions. The linguistic expressions are replaced by the corresponding TFNs as shown in Table 5.5. The TFN corresponding to the performance of the AME '*i*' by expert 't' is denoted as $R_{it.}$

Table 5.5: Linguistic judgements for performance ratings (Vinodh *et al*., 2013)

Linguistic Expressions	Notation for expression	Corresponding TFN
Worst	W	(0,0.5,1.5)
Very Poor	VP	(1,2,3)
Poor	P	(2,3.5,5)
Fair	F	(3,5,7)
Good	G	(5,6.5,8)
Very Good	VG	(7,8,9)
Excellent	E	(8.5,9.5,10)

Step 4.2 *Determine the average fuzzy performance rating*

The integrated fuzzy performance rating of each AME (with respect to past, present and future time horizons) is calculated by aggregating the multiple decision inputs using the arithmetic mean method. The average performance rating of AME 'i' is denoted as R_i

$$R_i = \frac{\sum_{t=1}^{s} R_{it}}{s} \quad \forall i = 1, 2, \ldots, n$$

Step 5 *Determination of FAMI*

The FAMI for an agile manufacturing environment is calculated across each time horizon (past, present and future) using the expression mentioned below:

$$FAMI = \frac{\sum_{i=1}^{n} (W_i * R_i)}{\sum_{i=1}^{n} (W_i)}$$

where 'n' refers to the number of AMEs

Step 6 *Determination of Euclidean distance with predetermined agility levels*

The TFNs corresponding to predetermined agility levels are finalized in consultation with the experts in the CFT. These TFNs are largely environment specific and cannot be generalized. Then, the Euclidean distance of FAMI with these predetermined agility levels are computed using the expression mentioned below:

$$D\,(FAMI,\, AL_k) = \left\{ \sum_{x \varepsilon p} (f_{FAMI}(x) \text{ - } f_{AL_k}(x))^2 \right\}^{1/2}$$

where $f_{FAMI}(x)$ represents the fuzzy number corresponding to FAMI

$f_{AL_k}(x)$ represents the fuzzy number corresponding to Agility Level '*k*'

5.3.3 Application of the Proposed Methodology in an Indian Manufacturing Company

The proposed methodology detailed in Section 5.3.2 has been applied to an Indian manufacturing company 'ABC'. The name 'ABC' has been assigned to the organization for maintaining confidentiality upon the request from the senior executives of the organization. The organizations' primary products include boiler and boiler accessories. The organization is a large enterprise with a gross turnover exceeding INR 5000 crores. ABC believes that it has achieved agility by responding to customer orders rather than fabricating in anticipation of customer orders. ABC fulfils its customers' requirements based on customer demand in terms of different parameters such as cost, delivery, quality, reliability and safety. ABC provides product customization by varying the product features. ABC also exhibits significant sourcing flexibility by outsourcing (sub-contracting) to third party vendor when the demand is more, and by utilizing its own manufacturing capabilities when the demand is manageable. Five senior executives of the company, with more than 10 years' experience in the organization constituted the cross functional team (CFT) and were interviewed to map the agility as well as the AMEs of agile manufacturing from the perspective of the company. These five experts were designated as A, B, C, D and E to maintain confidentiality. The AMEs identified from extensive literature review were shown to these experts and these AMEs were confirmed to be very relevant to the manufacturing organization under consideration. The reason for choosing inside experts for evaluating their own organization instead of choosing an independent entity is related to the nature of some AME's identified in Section 3. AME's like "product and process automation", "devolution of authority", "information visibility and transparency" and "human resource management" may be difficult to be judged by an outside independent entity within a limited amount of time and might result in an inaccurate picture of the real situation. Company experts themselves would be able to provide a true evaluation of their organization along these AME's. Since the experts chosen to provide the weights and scores are highly experienced and in responsibilities of strategic importance and the purpose of conducting this study were completely explained to them, it can be considered with a high level of confidence that their opinions will reflect the true status of the organization along the agile manufacturing frontier. Four sets of data were obtained from each expert in the CFT. They include a pair-wise comparison matrix for assessing the weights of the AMEs using the scale mentioned in Table 5.2, and three sets of questionnaires for obtaining the past, present and the future expected performance of the AMEs. Discussions were undertaken with the CFTs to determine the agility levels, their relevance to the manufacturing organization and their corresponding TFNs. Five predetermined agility levels, namely extremely agile, very agile, satisfactorily agile, fairly agile and slowly becoming agile were identified on the basis of discussions with the CFT. The predetermined agility levels along with their corresponding TFNs are shown in Table 5.6. The methodology is not complex and manual calculations are possible. However, to reduce computation time and make calculation faster, the fuzzy synthetic extent of the weights of the AMEs are calculated using user-friendly software developed using C# with the help of Microsoft Visual Studio Integrated Development Environment. A desktop application was also developed for ease of use in performing the analysis of the weights of the AMEs. The average fuzzy ratings, subsequent FAMI values and the Euclidean distance from the various predetermined agility levels were calculated with the help of basic commands and operations in Microsoft Excel 2010. The next section presents the results of the various analyses and the FAMI for the past, present and the expected future performance of the organization.

Table 5.6: Triangular fuzzy numbers corresponding to different agility levels (AL)

Agility level (AL_k)	**Notation for AL_k**	**Corresponding TFN** $f_{AL_k(x)}$
Extremely agile	EA	(7,8.5,10)
Very agile	VA	(5.5,7,8.5)
Satisfactorily agile	A	(3.5,5,6.5)
Fairly agile	F	(1.5,3,4.5)
Slowly becoming agile	S	(0,1.5,3)

Source: Vinodh *et al*. (2013)

5.3.4 Results

Pair-wise comparison matrices of the importance weights of AMEs were obtained from each expert. The pair-wise comparison matrix of expert A is provided in Table 5.7. The consistency of each pair-wise comparison matrix is checked and the judgements should be reworked by the respective experts in case the comparison matrices provided by them are found inconsistent. The consistency ratio (CR) for the pair-wise comparison matrix provided by expert A is 0.015. Since CR < 0.1, the pair-wise matrix provided by expert A is consistent. The fuzzified pair-wise comparison matrix for expert A is provided in Table 5.8. In the same manner, the pair-wise comparison matrices provided by all experts are fuzzified. The integrated fuzzified pair-wise comparison matrices for all the experts are then calculated (see Table 5.9). Then, the fuzzy synthetic extent of each enabler is calculated and it is provided in Table 5.10. The fuzzy performance rating for each enabler is obtained (for past, present and future expectation) in terms of linguistic expressions (worst, very poor, poor, fair, good, very good and excellent) from all the experts. The linguistic expressions obtained from the experts for the present performance of these AMEs is shown in Table 5.11. These linguistic expressions are then converted into the appropriate triangular fuzzy number (TFN). Table 5.12 shows the present performance rating of the AMEs in terms of their TFN equivalent and the average fuzzy performance ratings (APRs) for all AMEs. This process is repeated for the past performance as well as the future expected performance of these AMEs. Table 5.13 shows the fuzzy synthetic extent of the weights of the AMEs as well as the average performance rating of the AMEs, for the past, present and future time periods. The FAMI is then calculated for each time period and the Euclidean distance from the predetermined agility levels are also determined for all three time periods. These results are tabulated in Table 5.14. A sample step by step calculation of FAMI shown in the end of the Chapter.

5.4 Managerial Implications

The primary implication of this study was that manufacturing agility of the case organization over three time periods, namely past, present and future was mapped. The study showed that FAMI values were increasing steadily over the three time periods. The expected FAMI value for the future performance of the organizations along the lines of the manufacturing agility was (5.36, 6.76, 8.07), which indicates a better performance than the present performance which was mapped at (4.11, 5.56, 6.91). The present performance also showed improvement from the past performance of the organization which put the FAMI value at (1.50, 2.64, 3.8). In order to provide more absolute measures of the agility, the Euclidean distance of the FAMI values and predetermined agility levels were calculated. This measure of providing closeness to agility levels is easy to comprehend and also easy to calculate. The FAMI value for the past performance had the minimum distance of 0.78 to the level 'Fairly Agile'. So, the performance of the organization was assessed as 'Fairly Agile' for the past period. Next, the FAMI value of present performance had the minimum distance of 0.93 to the level 'Satisfactorily Agile'. Therefore, the present performance of the organization was assessed as 'Satisfactorily Agile'. Finally, the FAMI value corresponding to the expected future performance of the organization had the minimum distance of 0.51 to the agility level ‘Very Agile’. With this information, the managers can clearly monitor the progress of their organizations towards achieving agility. By looking at the Euclidean distance values, the managers can ascertain that the organization is progressing towards the ‘Extremely Agile’ status. Any deviation or lack of expected performance will be reflected in this metric and managers can immediately take corrective action. Also, the pair-wise comparison matrices for obtaining the importance weights of the AMEs give an opportunity for decision makers to compare the importance of one enabler over another. Suitable caution has to be exercised in interpreting the results of the study. The decision on the current agility level of the enterprise is decided by the distance of the FAMI and the predetermined agility levels. The closest distance is then determined and the agility level of the organization is assumed to be the agility level corresponding to the closest distance. But, a suitable threshold value for this distance needs to be determined by the experts. Any value above this threshold value, even if it is the minimum distance, should not be interpreted as the agility level for the organization. For example, consider an organization with a minimum Euclidean distance value of 2 (two) to the agility level ‘Very Agile’. Although, it is the minimum among all distances, the organization is still far from achieving the ‘Very Agile’ status. Therefore, a threshold value of, say 1 (one) is kept. Therefore, values more than ‘1’, even if they are minimal are summarily not considered. Even in our case organization the minimum Euclidean distance value for the present performance is 0.93, which indicates further scope for improvement. This distance is in the zone for being termed ‘Satisfactorily Agile’, but this distance can be further reduced. Managers can further continue with the process of fuzzy AHP instead of terminating at the fuzzy synthetic extent stage in order to determine the importance orders of the AMEs considered. This will provide them with an idea of the AMEs that needs to be improved or worked upon in order to improve the agility of the enterprise.

5.5 Conclusions

A methodology for measuring the agility of the enterprise by combining the fuzzy synthetic extent of AMEs weight and the average fuzzy performance ratings of the AMEs was proposed. A Fuzzy Agile Manufacturing Index (FAMI) was developed and its distance with predetermined agility levels was determined. This paper, therefore builds upon previous attempts to measure agility by proposing a method which would enable comparison of the AMEs in order to provide their respective importance weights. Also, consistency was checked to ensure that the data used for our study was consistent in every aspect. Also, provisions for measuring the agility at three intervals of time, namely, the past, present and the future were provided. The methodology was also applied to an Indian manufacturing organization and it was found that the agility of the organization has improved from the past and it is also expected that it will continue to improve in the future. The applications of fuzzy AHP as a multi criteria decision making tool are well known. Since the proposed methodology uses fuzzy AHP and combines them with the average performance ratings of the AME's to calculate the FAMI, this method is easy to use by industry experts as well as academics alike and does not require sophisticated tools for its deployment. Also, in case of a change in AMEs due to potential environmental changes, the proposed model can effectively calculate the manufacturing agility along the new AMEs with the expert opinion regarding the importance weights and performance of the new AMEs forming the input to the model. The combination of such characteristics makes the methodology attractive and implementable.

5.5.1 Limitations and Future Research

The proposed methodology in this paper also needs to be applied to different case organizations to see if the results can be replicated in different scenarios. Further, it has been assumed that the importance weights of the AMEs will remain constant over the past, present and future period. Manufacturing and business environments may change over the years and this might lead to the importance of AMEs also changing. For example, an enabler considered very important by the experts today might not be that important in the future. But, anticipation of the importance of the AMEs in the future is difficult. Therefore, this study may be modified to include changes in importance of the AMEs while computing the FAMI values. Also, future studies could be undertaken to empirically compare the proposed methodology and other existing methods for measuring agility in order to prove the utility of the proposed methodology. The links and correlation between agile manufacturing and the overall organizational performance could be probed.

Table 5.7: Pair-wise comparison matrix of AMEs weights for expert A

	ADP	PPA	SCI	CCT	SCP	DOA	IVT	MFM	CRM	SRM	HRM
ADP	1	3	1	2	3	4	2	2	5	4	1
PPA	1/3	1	1/3	1/2	1	2	1/2	1/2	3	2	1/3
SCI	1	3	1	2	3	4	2	2	4	4	1
CCT	1/2	2	1/2	1	2	3	1	1	3	2	1
SCP	1/3	1	1/3	1/2	1	2	1/2	1/2	4	2	1/3
DOA	1/4	1/2	1/4	1/3	1/2	1	1/2	1/3	2	1	1/4
IVT	1/2	2	1/2	1	2	2	1	1	3	3	1
MFM	1/2	2	1/2	1	2	3	1	1	3	3	1
CRM	1/5	1/3	1/4	1/3	1/4	1/2	1/3	1/3	1	1/2	1/5
SRM	1/4	1/2	1/4	1/2	1/2	1	1/3	1/3	2	1	1/5
HRM	1	3	1	1	3	4	1	1	5	5	1

Consistency Index (CI) = 0.02; Random CI = 1.51; Consistency Ratio (CR) = 0.01

Table 5.8: Fuzzified pair-wise comparison matrix of AMEs weights for expert A

Enabler	**Fuzzified inputs of the pair-wise comparison matrix of expert A {(P_{ijt}, Q_{ijt}, R_{ijt}) for every comparison of enabler '*i*' with enabler '*j*' and *t* = 1 (indicating expert 'A')}**
ADP	(1, 1, 1) (2, 3, 4) (1, 1, 2) (1, 2, 3) (2, 3, 4) (3, 4, 5) (1, 2, 3) (1, 2, 3) (4, 5, 6) (3, 4, 5) (1, 1, 2)
PPA	(0.25, 0.333, 0.5) (1, 1, 1) (0.25, 0.333, 0.5) (0.333, 0.5, 1) (1, 1, 2) (1, 2, 3) (0.333, 0.5, 1) (0.333, 0.5, 1) (2, 3, 4) (1, 2, 3) (0.25, 0.333, 0.5)
SCI	(0.5, 1, 1) (2, 3, 4) (1, 1, 1) (1, 2, 3) (2, 3, 4) (3, 4, 5) (1, 2, 3) (1, 2, 3) (3, 4, 5) (3, 4, 5) (1, 1, 2)
CCT	(0.333, 0.5, 1) (1, 2, 3) (0.333, 0.5, 1) (1, 1, 1) (1, 2, 3) (2, 3, 4) (1, 1, 2) (1, 1, 2) (2, 3, 4) (1, 2, 3) (1, 1, 2)
SCP	(0.25, 0.333, 0.5) (0.5, 1, 1) (0.25, 0.333, 0.5) (0.333, 0.5, 1) (1, 1, 1) (1, 2, 3) (0.333, 0.5, 1) (0.333, 0.5, 1) (3, 4, 5) (1, 2, 3) (0.25, 0.333, 0.5)
DOA	(0.2, 0.25, 0.333) (0.333, 0.5, 1) (0.2, 0.25, 0.333) (0.25, 0.333, 0.5) (0.333, 0.5, 1) (1, 1, 1) (0.333, 0.5, 1) (0.25, 0.333, 0.5) (1, 2, 3) (1, 1, 2) (0.2, 0.25, 0.333)
IVT	(0.333, 0.5, 1) (1, 2, 3) (0.333, 0.5, 1) (0.5, 1, 1) (1, 2, 3) (1, 2, 3) (1, 1, 1) (1, 1, 2) (2, 3, 4) (2, 3, 4) (1, 1, 2)
MFM	(0.333, 0.5, 1) (1, 2, 3) (0.333, 0.5, 1) (0.5, 1, 1) (1, 2, 3) (2, 3, 4) (0.5, 1, 1) (1, 1, 1) (2, 3, 4) (2, 3, 4) (1, 1, 2)
CRM	(0.167, 0.2, 0.25) (0.25, 0.333, 0.5) (0.2, 0.25, 0.333) (0.25, 0.333, 0.5) (0.2, 0.25, 0.333) (0.333, 0.5, 1) (0.25, 0.333, 0.5) (0.25, 0.333, 0.5) (1, 1, 1) (0.333, 0.5, 1) (0.167, 0.2, 0.25)
SRM	(0.2, 0.25, 0.333) (0.333, 0.5, 1) (0.2, 0.25, 0.333) (0.333, 0.5, 1) (0.333, 0.5, 1) (0.5, 1, 1) (0.25, 0.333, 0.5) (0.25, 0.333, 0.5) (1, 2, 3) (1, 1, 1) (0.167, 0.2, 0.25)
HRM	(0.5, 1, 1) (2, 3, 4) (0.5, 1, 1) (0.5, 1, 1) (2, 3, 4) (3, 4, 5) (0.5, 1, 1) (0.5, 1, 1) (4, 5, 6) (4, 5, 6) (1, 1, 1)

Table 5.9: Integrated fuzzified pair-wise comparison matrix for all experts

Enabler	Integrated Fuzzified inputs of the pair-wise comparison matrices for all experts {(a_{ij},b_{ij},c_{ij}) for every comparison of enabler '*i*' with enabler '*j*'}
ADP	(1, 1, 1) (1.32, 2.352, 3.366) (1, 1, 2) (1, 2, 3) (2, 3, 4) (3, 4, 5) (1, 1.32, 2.352) (1, 1.516, 2.551) (3.776, 4.782, 5.785) (2.169, 3.178, 4.183) (1, 1, 2)
PPA	(0.297, 0.425, 0.758) (1, 1, 1) (0.297, 0.425, 0.758) (0.644, 0.758, 1.516) (1, 1.516, 2.551) (1.149, 2.169, 3.178) (0.333, 0.5, 1) (0.517, 0.758, 1.431) (1.741, 2.408, 3.482) (0, 0, 0) (0.28, 0.392, 0.66)
SCI	(0.5, 1, 1) (1.32, 2.352, 3.366) (1, 1, 1) (1, 2, 3) (2, 3, 4) (3, 4, 5) (1, 1.32, 2.352) (1, 1.516, 2.551) (3.366, 4.373, 5.378) (2.169, 3.178, 4.183) (1, 1, 2)
CCT	(0.333, 0.5, 1) (0.66, 1.32, 1.552) (0.333, 0.5, 1) (1, 1, 1) (1, 2, 3) (1.32, 2.352, 3.366) (0.517, 0.66, 1.32) (0.644, 0.758, 1.516) (1.741, 2.766, 3.776) (1, 2, 3) (0, 0, 0)
SCP	(0.25, 0.333, 0.5) (0.392, 0.66, 1) (0.25, 0.333, 0.5) (0.333, 0.5, 1) (1, 1, 1) (1, 2, 3) (0.28, 0.392, 0.66) (0.297, 0.425, 0.758) (1.246, 2.297, 3.323) (1, 1.149, 2.169) (0.25, 0.333, 0.5)
DOA	(0.2, 0.25, 0.333) (0.315, 0.461, 0.871) (0.2, 0.25, 0.333) (0.297, 0.425, 0.758) (0.333, 0.5, 1) (1, 1, 1) (0.245, 0.33, 0.517) (0.257, 0.349, 0.561) (0.699, 0.956, 1.552) (0.488, 0.608, 1.149) (0.186, 0.229, 0.297)
IVT	(0.425, 0.758, 1) (1, 2, 3) (0.425, 0.758, 1) (0.758, 1.516, 1.933) (1.516, 2.551, 3.565) (1.933, 3.031, 4.076) (1, 1, 1) (1, 1.149, 2.169) (2.639, 3.758, 4.816) (1.741, 2.766, 3.776) (0.803, 0.871, 1.741)
MFM	(0.392, 0.66, 1) (0.699, 1.32, 1.933) (0.392, 0.66, 1) (0.66, 1.32, 1.552) (1.32, 2.352, 3.366) (1.783, 2.862, 3.898) (0.461, 0.871, 1) (1, 1, 1) (2.297, 3.393, 4.441) (1.516, 2.551, 3.565) (0.608, 0.699, 1.32)
CRM	(0.173, 0.209, 0.265) (0.287, 0.415, 0.574) (0.186, 0.229, 0.297) (0.265, 0.361, 0.574) (0.301, 0.435, 0.803) (0.644, 1.046, 1.431) (0.208, 0.266, 0.379) (0.225, 0.295, 0.435) (1, 1, 1) (0.415, 0.574, 1.149) (0.173, 0.209, 0.265)
SRM	(0.239, 0.315, 0.461) (0, 0, 0) (0.239, 0.315, 0.461) (0.333, 0.5, 1) (0.461, 0.871, 1) (0.871, 1.644, 2.048) (0.265, 0.361, 0.574) (0.28, 0.392, 0.66) (0.871, 1.741, 2.408) (1, 1, 1) (0.231, 0.301, 0.435)
HRM	(0.5, 1, 1) (1.516, 2.551, 3.565) (0.5, 1, 1) (0, 0, 0) (2, 3, 4) (3.366, 4.373, 5.378) (0.574, 1.149, 1.246) (0.758, 1.431, 1.644) (3.776, 4.782, 5.785) (2.297, 3.323, 4.338) (1, 1, 1)

Table 5.10: Fuzzy synthetic extent of the AMEs

Enabler	m_i^-	$\mathbf{m_i}$	m_i^+
ADP	0.08	0.154	0.317
PPA	0.032	0.064	0.147
SCI	0.076	0.152	0.304
CCT	0.038	0.085	0.185
SCP	0.028	0.058	0.13
DOA	0.019	0.033	0.075
IVT	0.058	0.124	0.252
MFM	0.049	0.109	0.216
CRM	0.017	0.031	0.06
SRM	0.021	0.046	0.09
HRM	0.072	0.145	0.26

Table 5.11: AME Performance in terms of linguistic expression from experts

AMEs	A (R_{i1})	B (R_{i2})	C (R_{i3})	D (R_{i4})	E (R_{i5})
Adaptability (ADP)	G	G	VG	G	E
Product and Process Automation (PPA)	VG	G	F	G	F
Supply Chain Integration (SCI)	VP	VP	P	F	F
Core Competency (CCT)	G	VG	G	G	VG
Supply Chain Key Partner's Alacrity (SCP)	P	P	VP	F	G
Devolution of Authority (DOA)	G	VG	VG	VG	G
Information Visibility and Transparency (IVT)	F	F	P	F	G
Manufacturing Management (MFM)	F	VG	G	G	VG
Customer Relationship Management (CRM)	VG	VG	E	VG	E
Supplier Relationship Management (CRM)	G	G	VG	VG	F
Human Resource Management (HRM)	P	VP	F	F	VP

(where R_{i1}, R_{i2}, R_{i3}, R_{i4} and R_{i5} indicate the performance ratings of AME 'i' obtained from experts 1, 2, 3, 4 and 5 respectively)

Table 5.12: TFN equivalent of present performance ratings and APR

AMEs	**A (R_{i1})**	**B (R_{i2})**	**C (R_{i3})**	**D (R_{i4})**	**E (R_{i5})**	**APR (R_i)**
ADP	(5, 6.5, 8)	(5, 6.5, 8)	(7, 8, 9)	(5, 6.5, 8)	(8.5, 9.5, 10)	(6.1, 7.4, 8.6)
PPA	(7, 8, 9)	(5, 6.5, 8)	(3, 5, 7)	(5, 6.5, 8)	(3, 5, 7)	(4.6, 6.2, 7.8)
SCI	(1, 2, 3)	(1, 2, 3)	(2, 3.5, 5)	(3, 5, 7)	(3, 5, 7)	(2, 3.5, 5)
CCT	(5, 6.5, 8)	(7, 8, 9)	(5, 6.5, 8)	(5, 6.5, 8)	(7, 8, 9)	(5.8, 7.1, 8.4)
SCP	(2, 3.5, 5)	(2, 3.5, 5)	(1, 2, 3)	(3, 5, 7)	(5, 6.5, 8)	(2.6, 4.1, 5.6)
DOA	(5, 6.5, 8)	(7, 8, 9)	(7, 8, 9)	(7, 8, 9)	(5, 6.5, 8)	(6.2, 7.4, 8.6)
IVT	(3, 5, 7)	(3, 5, 7)	(2, 3.5, 5)	(3, 5, 7)	(5, 6.5, 8)	(3.2, 5, 6.8)
MFM	(3, 5, 7)	(7, 8, 9)	(5, 6.5, 8)	(5, 6.5, 8)	(7, 8, 9)	(5.4, 6.8, 8.2)
CRM	(7, 8, 9)	(7, 8, 9)	(8.5, 9.5, 10)	(7, 8, 9)	(8.5, 9.5, 10)	(6.5, 7.7, 8.8)
SRM	(5, 6.5, 8)	(5, 6.5, 8)	(7, 8, 9)	(7, 8, 9)	(3, 5, 7)	(5.4, 6.8, 8.2)
HRM	(2, 3.5, 5)	(1, 2, 3)	(3, 5, 7)	(3, 5, 7)	(1, 2, 3)	(2, 3.5, 5)

Table 5.13: Average performance ratings and FSE of AMEs weights

Time Period	**AMEs**	**Average performance ratings (R_i)**	**FSE of weights (W_i)**
Past Performance	ADP	(1.8, 3.2, 4.6)	(0.08, 0.154, 0.317)
	PPA	(0.6, 1.4, 2.4)	(0.032, 0.064, 0.147)
	SCI	(0.6, 1.4, 2.4)	(0.076, 0.152, 0.304)
	CCT	(2, 3.5, 5)	(0.038, 0.085, 0.185)
	SCP	(0.8, 1.7, 2.8)	(0.028, 0.058, 0.13)
	DOA	(2.6, 4.4, 6.2)	(0.019, 0.033, 0.075)
	IVT	(1.2, 2.3, 3.5)	(0.058, 0.124, 0.252)
	MFM	(0.6, 1.4, 2.4)	(0.049, 0.109, 0.216)
	CRM	(5, 6.5, 8)	(0.017, 0.031, 0.064)
	SRM	(4.6, 6.2, 7.8)	(0.021, 0.046, 0.09)
	HRM	(1.4, 2.6, 3.8)	(0.072, 0.145, 0.26)
Present Performance	ADP	(6.1, 7.4, 8.6)	(0.08, 0.154, 0.317)
	PPA	(4.6, 6.2, 7.8)	(0.032, 0.064, 0.147)
	SCI	(2, 3.5, 5)	(0.076, 0.152, 0.304)
	CCT	(5.8, 7.1, 8.4)	(0.038, 0.085, 0.185)
	SCP	(2.6, 4.1, 5.6)	(0.028, 0.058, 0.13)
	DOA	(6.2, 7.4, 8.6)	(0.019, 0.033, 0.075)
	IVT	(3.2, 5, 6.8)	(0.058, 0.124, 0.252)
	MFM	(5.4, 6.8, 8.2)	(0.049, 0.109, 0.216)
	CRM	(6.5, 7.7, 8.8)	(0.017, 0.031, 0.064)
	SRM	(5.4, 6.8, 8.2)	(0.021, 0.046, 0.09)
	HRM	(2, 3.5, 5)	(0.072, 0.145, 0.26)
Future Performance	ADP	(6.5, 7.7, 8.8)	(0.08, 0.154, 0.317)
	PPA	(5, 6.5, 8)	(0.032, 0.064, 0.147)
	SCI	(4.2, 5.6, 7)	(0.076, 0.152, 0.304)

Time Period	**AMEs**	**Average performance ratings (R_i)**	**FSE of weights (W_i)**
	CCT	(6.5, 7.7, 8.8)	(0.038, 0.085, 0.185)
	SCP	(5.4, 6.8, 8.2)	(0.028, 0.058, 0.13)
	DOA	(7.2, 8.3, 9.2)	(0.019, 0.033, 0.075)
	IVT	(5, 6.5, 8)	(0.058, 0.124, 0.252)
	MFM	(5.7, 7.1, 8.4)	(0.049, 0.109, 0.216)
	CRM	(7.2, 8.3, 9.2)	(0.017, 0.031, 0.064)
	SRM	(6.2, 7.4, 8.6)	(0.021, 0.046, 0.09)
	HRM	(3.8, 5.6, 7.4)	(0.072, 0.145, 0.26)

Table 5.14: Computed FAMI values and Euclidean distance to predetermined agility levels

Time Period	**FAMI**	**Agility levels (AL_k)**	***D* (FAMI, AL_k)**
Past Performance	(1.50, 2.64, 3.8)	Extremely Agile (EA)	10.15
		Very Agile (VA)	7.55
		Satisfactorily Agile (A)	4.10
		Fairly Agile (F)	**0.78**
		Slowly Becoming Agile (S)	2.04
Present Performance	(4.11, 5.56, 6.91)	Extremely Agile (EA)	5.14
		Very Agile (VA)	2.54
		Satisfactorily Agile (A)	**0.93**
		Fairly Agile (F)	4.38
		Slowly Becoming Agile (S)	6.99
Future Performance	(5.36, 6.76, 8.07)	Extremely Agile (EA)	3.07
		Very Agile (VA)	**0.51**
		Satisfactorily Agile (A)	3.00
		Fairly Agile (F)	6.47
		Slowly Becoming Agile (S)	9.06

Sample step by step calculation of FAMI

(The pair-wise comparison matrix of AMEs obtained from Expert "A" is shown in Table 5.7)

Step 3.2: To check consistency of pair-wise comparison matrices

Step 1 *Calculation of normalized pair-wise comparison matrix*

Table 5.15(A): Column-wise total of the pair-wise comparison matrix for Table 5.7

	ADP	PPA	SCI	CCT	SCP	DOA	IVT	MFM	CRM	SRM	HRM
ADP	1	3	1	2	3	4	2	2	5	4	1
PPA	1/3	1	1/3	1/2	1	2	1/2	1/2	3	2	1/3
SCI	1	3	1	2	3	4	2	2	4	4	1
CCT	1/2	2	1/2	1	2	3	1	1	3	2	1
SCP	1/3	1	1/3	1/2	1	2	1/2	1/2	4	2	1/3
DOA	1/4	1/2	1/4	1/3	1/2	1	1/2	1/3	2	1	1/4
IVT	1/2	2	1/2	1	2	2	1	1	3	3	1
MFM	1/2	2	1/2	1	2	3	1	1	3	3	1
CRM	1/5	1/3	1/4	1/3	1/4	1/2	1/3	1/3	1	1/2	1/5
SRM	1/4	1/2	1/4	1/2	1/2	1	1/3	1/3	2	1	1/5
HRM	1	3	1	1	3	4	1	1	5	5	1
Total	5.86	18.33	5.91	10.16	18.25	26.50	10.16	9.99	35.00	27.50	7.31

Table 5.15(B): Normalized pair-wise comparison matrix

	ADP	**PPA**	**SCI**	**CCT**	**SCP**	**DOA**	**IVT**	**MFM**	**CRM**	**SRM**	**HRM**
ADP	0.17	0.16	0.17	0.20	0.16	0.15	0.20	0.20	0.14	0.15	0.14
PPA	0.06	0.05	0.06	0.05	0.05	0.08	0.05	0.05	0.09	0.07	0.05
SCI	0.17	0.16	0.17	0.20	0.16	0.15	0.20	0.20	0.11	0.15	0.14
CCT	0.09	0.11	0.08	0.10	0.11	0.11	0.10	0.10	0.09	0.07	0.14
SCP	0.06	0.05	0.06	0.05	0.05	0.08	0.05	0.05	0.11	0.07	0.05
DOA	0.04	0.03	0.04	0.03	0.03	0.04	0.05	0.03	0.06	0.04	0.03
IVT	0.09	0.11	0.08	0.10	0.11	0.08	0.10	0.10	0.09	0.11	0.14
MFM	0.09	0.11	0.08	0.10	0.11	0.11	0.10	0.10	0.09	0.11	0.14
CRM	0.03	0.02	0.04	0.03	0.01	0.02	0.03	0.03	0.03	0.02	0.03
SRM	0.04	0.03	0.04	0.05	0.03	0.04	0.03	0.03	0.06	0.04	0.03
HRM	0.17	0.16	0.17	0.10	0.16	0.15	0.10	0.10	0.14	0.18	0.14

Step 2 *Calculation of principal vector*

Table 5.16: Principal vector corresponding to pair-wise comparison matrix obtained from expert 'A'

AME	Calculation of PV	Elements of PV
ADP	(0.17+0.16+0.17+0.20+0.16+0.15+0.20+0.20+0.14+0.15+0.14)/11	0.17
PPA	(0.06+0.05+0.06+0.05+0.05+0.08+0.05+0.05+0.09+0.07+0.05)/11	0.06
SCI	(0.17+0.16+0.17+0.20+0.16+0.15+0.20+0.20+0.11+0.15+0.14)/11	0.16
CCT	(0.09+0.11+0.08+0.10+0.11+0.11+0.10+0.10+0.09+0.07+0.14)/11	0.10
SCP	(0.06+0.05+0.06+0.05+0.05+0.08+0.05+0.05+0.11+0.07+0.05)/11	0.06
DOA	(0.04+0.03+0.04+0.03+0.03+0.04+0.05+0.03+0.06+0.04+0.03)/11	0.04
IVT	(0.09+0.11+0.08+0.10+0.11+0.08+0.10+0.10+0.09+0.11+0.14)/11	0.10
MFM	(0.09+0.11+0.08+0.10+0.11+0.11+0.10+0.10+0.09+0.11+0.14)/11	0.10
CRM	(0.03+0.02+0.04+0.03+0.01+0.02+0.03+0.03+0.03+0.02+0.03)/11	0.03
SRM	(0.04+0.03+0.04+0.05+0.03+0.04+0.03+0.03+0.06+0.04+0.03)/11	0.04
HRM	(0.17+0.16+0.17+0.10+0.16+0.15+0.10+0.10+0.14+0.18+0.14)/11	0.14

Step 3 *Calculation of principal eigen value* λ_{max}, *CI* and *CR*

λ_{max}= (5.86*0.17) + (18.33*0.06) + (5.91*0.16) + (10.16*0.10) + (18.25*0.06) + (26.5*0.04) + (10.16*0.1) + (9.99&0.1) + (35*0.03) + (27.5*0.04) + (7.31*0.14)

λ_{max} = 11.25

Total number of entries in the pair-wise comparison matrix, N = 11

Consistency Index, $CI = (\lambda_{max} - N) / (N - 1) = 0.02$

Random Index (RI) corresponding to N = 11 (from Table 5.3) = 1.51

Consistency Ratio, $CR = CI / RI = 0.01$

Since CR < 10%, the judgements provided by Expert 'A' are considered to be consistent. The same procedure is repeated to check the consistency of judgements provided by all other experts.

Step 3.3: Fuzzify the pair-wise comparison matrix of each expert (Lee, 2009)

The fuzzification of crisp values provided by expert 'A' corresponding to enabler 'ADP' is shown in Table 5.17. The same procedure is repeated for all other enablers, and the crisp judgements provided by all other experts.

Table 5.17: Fuzzification of crisp judgement provided by expert 'A' corresponding to enabler 'ADP'

AME	Compared with	Crisp Judgement	TFN (Refer Table 5.4) $\{P_{1j1}, Q_{1j1}, R_{1j1}\}$
ADP	ADP	1	(1,1,1)
ADP	PPA	3	(3-1,3,3+1) = (2,3,4)
ADP	SCI	1	(1,1,2)
ADP	CCT	2	(2-1,2,2+1) = (1,2,3)
ADP	SCP	3	(3-1,3,3+1) = (2,3,4)
ADP	DOA	4	(4-1,4,4+1) = (3,4,5)
ADP	IVT	2	(2-1,2,2+1) = (1,2,3)
ADP	MFM	2	(2-1,2,2+1) = (1,2,3)
ADP	CRM	5	(5-1,5,5+1) = (4,5,6)
ADP	SRM	4	(4-1,4,4+1) = (3,4,5)
ADP	HRM	1	(1,1,2)

$\{P_{1j1}, Q_{1j1}, R_{1j1}\}$ represents the TFN corresponding to enabler 1 with enabler '*j*' for *j* = 1, 2,…,11 for expert 1

Step 3.4: Integrate the fuzzified pair-wise comparison matrices

This step combines the TFNs corresponding to the crisp judgement provided by experts 'A' to 'E' for the comparison of enabler 'i' and enabler 'j' into a single TFN. Consider the comparison of enabler 'ADP' with enabler 'PPA'. Table 5.18 represents the fuzzified inputs provided by experts 'A' to 'E'.

Table 5.18: Fuzzified inputs for comparison of enabler 'ADP' with 'PPA'

AME	Compared with	Expert	TFN
ADP	PPA	A	(2,3,4)
ADP	PPA	B	(1,2,3)
ADP	PPA	C	(1,2,3)
ADP	PPA	D	(1,2,3)
ADP	PPA	E	(2,3,4)

$\{P_{12t}, Q_{12t}, R_{12t}\}$ refers to the TFN corresponding to the comparison of enabler 1 with enabler 2 for *t* = 1,2,3,4,5

The integrated TFN (a_{12}, b_{12}, c_{12}) for the comparison of enabler 'ADP' with enabler 'PPA' can be calculated as shown below (refer step 3.4 in Section 5.3.2)

$a_{12} = (P_{121}*P_{122}*P_{123}*P_{124}*P_{125}) \wedge (1/5) = (2*1*1*1*2) \wedge (1/5) = 1.15$

$b_{12} = (Q_{121}*Q_{122}*Q_{123}*Q_{124}*Q_{125}) \wedge (1/5) = (3*2*2*2*3) \wedge (1/5) = 2.35$

$c_{12} = (R_{121}*R_{122}*R_{123}*R_{124}*R_{125}) \wedge (1/5) = (4*3*3*3*4) \wedge (1/5) = 3.36$

Step 3.5: Determine the FSE of AME

The integrated fuzzified pair-wise comparison matrix for the comparison of enabler 'i' with enabler 'j' for all experts is shown in Table 5.9. The integrated TFN corresponding to the comparison of enabler 'i' with enabler 'j' is denoted as (a_{ij}, b_{ij}, c_{ij}).

An example to show the calculation of FSE of enabler 'ADP' is shown. From Table 5.9:

$$
\begin{aligned}
W_1 &= \left(m_1^-, \quad m_1 \quad m_1^+\right) \\
&= \left\{ \frac{\sum_{j=1}^{n} a_{1j}}{\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}}, \quad \frac{\sum_{j=1}^{n} b_{1j}}{\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}}, \quad \frac{\sum_{j=1}^{n} c_{1j}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}} \right\} \\
&= \left\{ \frac{(1+1.32+\ldots+2.169+1)}{(1+3.366+\ldots+4.338+1)}, \quad \frac{(1+2.352+\ldots+3.178+1)}{(1+2.352+\ldots+3.323+1)}, \quad \frac{(1+3.366+\ldots+4.183+2)}{(1+1.32+\ldots+2.297+1)} \right\} \\
&= (0.08, 0.154, 0.317)
\end{aligned}
$$

Step 4.1: Capture the expert judgement on the performance rating of each AME

The expert judgement regarding the present performance of each AME has been shown in Table 5.11. Similarly the judgement regarding the past and the expected future performance of each AME is also captured.

Step 4.2: Determine the average performance rating (APR)

The expert judgement obtained in terms of linguistic expression for the present performance of AMEs has been shown in Table 5.12. An example to calculate the APR of ADP has been shown. The same procedure is repeated to calculate the APRs of all other AMEs for all time horizons.

Table 5.19: Present performance rating of ADP obtained from all experts

AME	A (R_{11})	B (R_{12})	C (R_{13})	D (R_{14})	E (R_{15})
ADP	(5, 6.5, 8)	(5, 6.5, 8)	(7, 8, 9)	(5, 6.5, 8)	(8.5, 9.5, 10)

R_{11} represents the performance rating of enabler '1' according to expert 1 and so on

Average performance rating (APR) of ADP

$$= \left\{ \frac{(5+5+\ldots+8.5)}{5}, \quad \frac{(6.5+6.5+\ldots+9.5)}{5}, \quad \frac{(8+9+\ldots+10)}{5} \right\}$$

APR of ADP = (6.1, 7.4, 8.6)

Step 5 Determination of FAMI

This step combines the results obtained in step 4.2 and step 3.5 to calculate the fuzzy agile manufacturing index (FAMI). A sample calculation to derive the FAMI for the agile manufacturing environment for the present situation is shown. The same procedure is repeated for both past and future time horizons.

Table 5.20: APRs of all AMEs for present situation and FSEs of all AMEs weights

Time Period	**AMEs**	**Average Performance Ratings (R_i) {From Step 4.2}**	**FSE of weights (W_i) {From Step 3.5}**
Present Performance	ADP	(6.1, 7.4, 8.6)	(0.08, 0.154, 0.317)
	PPA	(4.6, 6.2, 7.8)	(0.032, 0.064, 0.147)
	SCI	(2, 3.5, 5)	(0.076, 0.152, 0.304)
	CCT	(5.8, 7.1, 8.4)	(0.038, 0.085, 0.185)
	SCP	(2.6, 4.1, 5.6)	(0.028, 0.058, 0.13)
	DOA	(6.2, 7.4, 8.6)	(0.019, 0.033, 0.075)
	IVT	(3.2, 5, 6.8)	(0.058, 0.124, 0.252)
	MFM	(5.4, 6.8, 8.2)	(0.049, 0.109, 0.216)
	CRM	(6.5, 7.7, 8.8)	(0.017, 0.031, 0.064)
	SRM	(5.4, 6.8, 8.2)	(0.021, 0.046, 0.09)
	HRM	(2, 3.5, 5)	(0.072, 0.145, 0.26)

$$\{FAMI\}_{Present} = \left\{ \begin{array}{l} \frac{(6.1*0.08)+(4.6*0.032)\ldots+(2*0.072)}{(0.08+0.032+\ldots+0.072)}, \\ \frac{(7.4*0.154)+(6.2*0.064)\ldots+(3.5*0.145)}{(0.154+0.064+\ldots+0.145)}, \\ \frac{(8.6*0.317)+(7.8*0.147)\ldots+(5*0.26)}{(0.317+0.147+\ldots+0.26)} \end{array} \right\} = (4.11,5.56,6.91)$$

Step 6 Determination of Euclidean distance with predetermined agility levels

The predetermined agility levels along with their corresponding TFNs are shown in Table 5.6. Considering the FAMI of the present environment as an example, the Euclidean distance is calculated as shown below. The same procedure is repeated for calculating the Euclidean distance corresponding to the FAMIs of other environments (past and future)

Table 5.21: Euclidean distance of FAMI

Distance of FAMI with	**Calculation**	**Result**
Extremely agile	$\sqrt{\left[(4.11-7)^2+(5.56-8.5)^2+(6.91-10)^2\right]}$	5.14
Very agile	$\sqrt{\left[(4.11-5.5)^2+(5.56-7)^2+(6.91-8.5)^2\right]}$	2.54
Satisfactorily agile	$\sqrt{\left[(4.11-3.5)^2+(5.56-5)^2+(6.91-6.5)^2\right]}$	0.93
Fairly agile	$\sqrt{\left[(4.11-.1.5)^2+(5.56-3)^2+(6.91-4.5)^2\right]}$	4.38
Slowly becoming agile	$\sqrt{\left[(4.11-0)^2+(5.56-1.5)^2+(6.91-3)^2\right]}$	6.99

CHAPTER 6

Performance Analysis of Agile Manufacturing

6.1 Introduction

In the current business environment, manufacturing organizations have to develop and acquire the capability to predict, understand and react to global competition, ever changing and increasingly unpredictable customer demands, advanced technologies, reduced product life cycle etc., for its survival and growth. Agile manufacturing is defined as the ability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer designed products and services (Gunasekaran, 1998). It is highly capable of developing new products and providing customization opportunities in an efficient manner (Hallgren and Olhager, 2009). It is also seen as more pro-active than reactive to customer needs, being considered as customer oriented management approach (Castro *et al.,* 2012). Agile manufacturing requires full integration of highly trained, motivated and empowered employees working in teams; the use of advanced design, manufacturing and administrative technologies; integration of operations with suppliers and customers; concurrent engineering; and knowledge management (Vazquez-Bustelo *et al.*, 2007). Hence it is obvious that AM requires huge investments in different areas in order to enhance the agility and therefore, its impact on business performance needs to be studied, monitored and evaluated to justify such investments. A methodology is developed using both Fuzzy Analytic Hierarchy Process (FAHP) and Performance Value Analysis (PVA) to evaluate and analyze the agile manufacturing performance along the timeline. The FAHP was proposed to determine the importance of key performance indicators for different outcomes whereas PVA is used to evaluate and analyze agile manufacturing performance. A Graph Theoretic Approach (GTA) was also developed to quantify, evaluate and compare the implementation performance of Agile Manufacturing (AM) program along Agile Manufacturing Enablers (AMEs) at different timeline. Broadly eleven Agile Manufacturing Enablers (AMEs) were identified and classified into three Significant Categories (SCs). The analysis was further extended to evaluate the performance along the timeline and eventually compare the results with different performance scenarios to set the future targets.

Section 6.2 provides literature review of performance analysis along outcomes and their corresponding key performance indicators of agile manufacturing. The performance analysis of agile manufacturing along significant areas is carried out in Section 6.3. Section 6.3.1 presents a methodology for performance analysis of agile manufacturing while Section 6.3.2 develops the case situation for the proposed methodology. Section 6.3.3 and Section 6.3.4 discuss the results and the managerial implications respectively while Section 6.4 deals with performance analysis of agile manufacturing enablers. Section 6.5 concludes the agile manufacturing performance analysis with a direction for future research.

6.2 Literature Review of Performance Analysis of Agile Manufacturing

Agile manufacturing is a term applied to an organization that has created the processes, tools, and training to enable it to respond quickly to customer needs and market changes while still controlling cost and quality (Volkner and Werners, 2000). Agile has the higher potential and it can be serve as an instrument for starting "a journey" towards new sustainable organizational paradigms (Putnik and Putnik, 2012). Although the lean manufacturing approach has been considered in many past and present programs, analysis of the most recent programs shows a greater priority is given to the AM approach (Castro *et al.,* 2012). It has positive impact on financial performance (Yusuf and Adeleye, 2002, Vazquez-Bustelo *et al*., 2007 and Inman *et al*., 2011). It also improves both operational and financial performance (by developing manufacturing strength) whereas the greatest impact is noted in market performance (Vazquez-Bustelo *et al.,* 2007). The literature suggests that various researchers have studied various aspects of AM performance and applied different analytical tools to analyze it. Gunasekaran *et al.* (2002) developed an agility audit questionnaire on AM in the GEC-Marconi Aerospace (GECMAe) company for assessing the agility level of the company. They reported GECMAe's AM experience including a list of recommendations for improving its competitiveness and a framework has been formulated to highlight the present situation and future directions. Cao and Dowlatshahi (2005) developed a conceptual framework to systematically explore the relationship between AM and business performance and validated empirically taking inputs from managers of the United States manufacturing companies. They concluded that the synergy and interaction among the enablers of AM could be more of a determining factor for success of AM than the individual enablers. Adeleye and Yusuf (2006) conducted a survey by questionnaire administered to 600 companies and validated through statistical tests that flexibility is superior to leanness but that it may add more to costs than to revenue. They also suggested that flexibility can be achieved by AM. Agarwal *et al.* (2006) developed a framework to encapsulate the market sensitiveness, process integration, information driver and flexibility measures of supply chain performance using Analytic Network Process (ANP) approach. They explored the relationship among lead-time, cost, quality, and service level and the leanness and agility of a case supply chain in fast moving consumer goods business. Vazquez-Bustelo *et al.* (2007) analyzed the impact of AM on the success of different industries in Spain along different dimensions and concluded that in turbulent environments, the integrated use of AM practices promotes manufacturing competitive strength, leading to better operational, market and financial performance. Zerenler (2007) explored the relationship between the agility and business performance and the effect of the alignment between AM and IT on business performance in the textile industry. The results were found to be all statistically significant. Hallgren and Olhager (2009) carried out an empirical survey of leanness and agility simultaneously, using data from manufacturing firms in Europe, Asia, and North America. They found that the major differences in performance outcomes are related to cost and flexibility, such that lean manufacturing has a significant impact on cost performance (whereas AM has not), and that AM has a stronger relationship with volume as well as product mix flexibility than does lean manufacturing. Vinodh *et al.* (2010) designed a model named as agile customization programme amalgamating mass customization and principles of AM. They implemented in an electronic switches manufacturing company situated in India and found that it would lead to better competitiveness and core competencies. They have also suggested that the performance of this programme in the implemented companies shall be measured using AM metrics such as responsiveness, time compression, quality improvement and profitability. Jacobs *et al.* (2011) statistically established that product modularity facilitates process modularity, engenders manufacturing agility, and improves growth performance in ROI (Return on Investment), ROS (Return on Sale), and market share taking inputs from first tier suppliers to the ‘‘Big Three’’ auto manufacturers in North America. Inman *et al.* (2011) developed AM performance model using structural equation modeling methodology taking data from production and operations managers working for large U.S. manufacturers. They concluded that AM had a direct positive relationship with the operational performance of the firm and the operational performance of the firm has a direct positive relationship with the marketing performance of the firm whereas the positive relationship between the operational performance of the firm and the financial performance of the firm is mediated by the marketing performance of the firm. Yauch (2011) constructed a quantitative, objective metric for agility performance that assesses agility as a performance outcome, capturing both organizational success and environmental turbulence, and applicable to manufacturing organizations of all types. Routroy and Shankar (2015) combined Fuzzy Analytic Hierarchy Process (FAHP) and Performance Value Analysis (PVA) to analyse an apparel supply chain supply chain performance along the time. Harraf *et al*. (2015) developed an organizational agility framework that is grounded on ten pillars (i.e. culture of innovation, empowerment, tolerance or ambiguity, vision, change management, organizational communication, market analysis and response, operations management, structural fluidity and a learning organization). Sangari and Razmi (2015) carried out empirical study taking data from manufacturing companies working in the automotive industry in Iran and found that supply chain business intelligence competence have positive effects on agile capabilities and agile performance of the supply chain. Haq and Boddu (2015) discussed the importance of agility in food processing industries and proposed an analytic hierarchy process - based framework to improve its agility. Dev and Kumar (2016) proposed a set of critical success factors for evaluating AM in the manufacturing sector using AHP summarizing the multiple experts’ opinions. Many researchers have also recently used graph theory for performance evaluation in different areas such as performance assessment of transportation fuels (Lanjewar *et al*., 2015), performance of supplier development implementation (Routroy *et al.,* 2016), performance of sustainability enablers in a manufacturing organization (Jayakrishna *et al*., 2016) and lean manufacturing (Kumar and Kumar, 2016). However, the graph theory approach does not check the consistency of the judgement and also not able to capture the importance of key performance indicators. Therefore, a methodology (see Section 6.3.1) was proposed using both FAHP and PVA to evaluate and analyze the AM performance along the timeline.

6.3 Significant Areas of Agile Manufacturing for Performance Analysis

An extensive literature review has been carried out regarding Significant Areas (SAs) of AM for performance analysis and also industry experts of Indian manufacturing industries were consulted regarding this issue. Finally, eight SAs (i.e. Manufacturing Performance (MP), Financial Performance (FP), Marketing Performance (MP), Product Development (PD), Customer Satisfaction (CS), Bottom Line Performance (BP), Top Line Performance (TP) and Supply Chain Performance (SP)) were selected for performance analysis of AM. For each SA, Key Performance Indicators (KPIs) (See Table 6.1) are identified on the basis of literature and discussion held with the experts from Indian Industries. The details of each significant area are mentioned below:

Manufacturing Performance: It refers to manufacturing performances like reduced makespan (time to complete all operations), reduced order response times (time from getting an order and fulfilling it), rapid changeover times (from one product variant or type to next), reduced cycle times (MLT) and costs, ability to produce high product varieties, encourages customization of modular manufacturing and manufacturing competitive strength.

Financial Performance: It refers to the financial outcomes in the form of economic stability due to sustained revenue generation.

Marketing Performance: It refers to marketing outcomes in the form of improved performances in market share, response times and managing the changes in customer demands.

Product Development Performance: It refers to the outcomes in product development in the form of product management, product variety, new product development, product reconfiguration and design collaboration.

Customer Satisfaction Performance: It refers to the customer satisfaction indicators and it includes performance indicators such as customer requirements fulfilled, customer delight, customer retention and customer base enhancement.

Bottom Line Performance: It refers to the outcomes in the manufacturing operations and the focus is on improving operational performances and being cost effective. It includes performance indicators such as operational performance, operational cost effectiveness and operational effectiveness.

Top Line Performance: It refers to the agility performance at an organizational/strategic level. It includes overall performance along learning, innovation, organizational culture, competitive advantage, company's overall performance etc.

Supply Chain Performance: It refers to the agility performance of upstream (i.e. supply side) and downstream members of the supply chain. It includes overall performance along relationships, innovation flow, information visibility, robustness of the system etc.

Table 6.1: Outcomes and key performance indicators of agile manufacturing

Outcome	**Key Performance Indicator**	**References**
Manufacturing Performance (MP)	Customization (CUS)	Panayiotis and Ross, 2009; Daniel *et al.,* 2007; Ching *et al.,* 2006; Ramesh and Devadasan, 2007; Roger *et al.,* 1997; Aruo, 2009 and discussion held with experts.
	Manufacturing capability (MAC)	
	Manufacturing cost (MCO)	
	Manufacturing time (MTI)	
	Change over time (COT)	
	Process reconfiguration (PRE)	
Financial Performance (FP)	Profit margin (PRM)	Calvo*et al.,* 2008; Aruo, 2009; Andrew *et al.,* (2012); Pham *et al.,* 2012; Shannon *et al.,* 2012 and discussion held with experts.
	Profit enhancement (PEN)	
	Economic stability (ECS)	
	Economic sustainability (ESU)	
Marketing Performance (MA)	Capturing market environment (CME)	Aruo, 2009, Mengoni and Mandorli, 2009; Ching *et al.,* 2006; Ramesh and Devadasan 2007; Vinodh*et al.,* 2008 and discussion held with experts.
	Management of market volatility (CMV)	
	Improvement in market share (IMS)	
	Entering new market (ENM)	
	Response time for customer orders and queries (RTC)	
	Quick response to market changes (QRM)	
Product Development Performance (PD)	Product Management (PMA)	Ching*et al.,* 2006, Ramesh and Devadasan 2007; Vinodh*et al.,* 2008; Mengoni*et al.,* 2009; Aruo, 2009 and discussion held with experts.
	Product variety (PRV)	
	Development of new product (DNP)	
	Product reconfiguration (PTR)	
	Design collaboration (DEC)	
Customer Satisfaction Performance (CS)	Customer requirements fulfilled (CRF)	Ching*et al.,* 2006; Subhash*et al.,* 2009 and discussion held with experts.
	Customer delight (CUD)	
	Customer retention (CUR)	
	Customer base enhancement (CBE)	

Outcome	Key Performance Indicator	References
Bottom Line Performance (BP)	Operational performance (OPE)	Daniel *et al.,* 2007; Vinodh*et al.,* 2008; Hetherington and Ismail, 2007 and discussion held with experts.
	Operational cost effectiveness (OCE)	
	Operational effectiveness (OCF)	
Top LinePerformance (TP)	Sustainable competitive advantage (SCA)	Hetherington and Ismail, 2007; Tian *et al.,* 2006; Shannon *et al.,* 2012; Ching*et al.,* 2006; Vinodh*et al.,* 2008; Charlene, 2007 and discussion held with experts.
	Company performance (CPE)	
	Level organizational learning (LOL)	
	Robust operations (ROP)	
	Fosters innovation (FIN)	
	Empowered work teams (EWT)	
	Job satisfaction (JSA)	
Supply Chain Performance (SP)	Upstream relationships (URE)	Vinodh*et al.,* 2008, Luis *et al.,* 2009; Daniel *et al.,* 2007, Gaafar and Masoud, 2005; Daniel *et al.,* 2007; Subhash*et al.,* 2009 and discussion held with experts.
	Downstream relationships (DRE)	
	Inventory turns ratio (ITR)	
	Innovation flow(INF)	
	Product introduction time (PIT)	
	Robust to market changes (RMC)	
	Information visibility (INV)	

6.3.1 Proposed Methodology for Performance Analysis of Agile Manufacturing

In the literature, one can find various methods/approaches used to evaluate/assess/measure agility of the system in general and also few works have also been reported for assessing and measuring agility in AM. But not much comprehensive research has been established to analyse the outcomes of AM along various significant areas. The performance analysis of AM outcomes in a specific business environment can establish the areas where efforts should be directed and also duration can be fixed for performance evaluation. After identifying the underperforming SA in general and within SA in specific, the corrective action can be initiated for improving them so as to enhance the AM performance. Therefore, a methodology is proposed combining FAHP and PVA to analyse the AM performance at different point of time. FAHP is used to calculate the KPI considering the impact of each SA on AM and impact of each KPI on the corresponding SA. The PVA is applied to analyse the performance of the AM at different time periods capturing the AM performance along all the KPIs and their corresponding normalized weights at a specific time period. The combined AHP-PVA algorithm has been applied in various areas (Routroy, 2009, Routroy and Pradhan, 2012; Routroy and Pradhan, 2014; and Routroy and Shankar, 2015). Therefore, FAHP and PVA are combined and proposed for performance analysis of AM at different pre-specified time horizons.

The proposed methodology starts with the formation of expert groups comprising of experienced professional drawn from different major departments of the organization. The experts should have sound knowledge of AM and agility in general and in the case company in specific. Next, the various SAs should be identified taking inputs both from exhaustive literature review and discussion held with experts drawn from the case company. The KPIs of each SA should be fixed for each SA on the basis of the discussion with experts considering its relevance on SA. Then Fuzzy AHP (FAHP) should be applied to determine the normalized weight priority weights of all KPIs (as mentioned in Section 6.3.1.1). The time horizons for performance assessment should be fixed and also the desired performance for each KPI. The competitive benchmarking approach may be used for this. Then, the Performance Value Analysis (PVA) is proposed to capture, analyse and evaluate the performance of the AM along KPIs at different pre-specified time horizons and also desired performance level is calculated (as mentioned in Section 6.3.1.2.). Then, the performance gaps can be identified on the basis of current and desired performance which in turn will indicate the underperforming SAs in a particular time horizon. For the gap reduction across different identified areas, different strategies should be developed and implemented. Again the AM performance should be monitored at a pre-specified time period and this process should be repeated.

6.3.1.1 Development of FAHP to determine the normalized weights of KPIs

One can find the applications FAHP for decision making in different areas of manufacturing in general and AM in specific. Some of recent applications of FAHP in the area of AM include analyse and evaluate the agile suppliers (Beikkhakhian *et al*., 2015); prioritize agility dimensions in auto parts manufacturing company (Kazemi and Seyyedi, 2015); manufacturing resource evaluation and selection(Lu and Sheng, 2015); agility level of a manufacturing system (Routroy *et al*., 2015); performance analysis of agile supply chain (Routroy and Shankar, 2015); and measure the procurement performance in the automotive industry (Saad *et al*., 2016), risk assessment in green supply chain (Mangla, *et al.,* 2016) and sustainable business excellence index of a firm (Metaxas *et al.,* 2016). The steps of FAHP process used in this paper are described below:

Step 1 *Construct a two level hierarchy with the first level for the SA of AM and the second level for the KPIs of each SA.*

The identified SA of AM will be considered as first level. For each identified SA, the KPI established will be considered as second level.

Step 2 *Fix the number of experts or expert groups and construct pair wise comparison matrices for each SA and its corresponding KPIs*

The number of experts/expert groups to be considered should be fixed in the consultation with CFT. Each expert group will construct the pair wise comparison matrices for the SAs and also for their KPIs. The experts' judgements are captured in pair wise comparison matrices on a 1-9 scale (Saaty, 1980) (see Table 6.2).

Table 6.2: Scale for pair-wise comparisons (Saaty, 1980)

Intensity of importance	Definition and explanation
1	Equally important
2	Equally to moderate more important
3	Moderately more important
4	Moderate to strong more important
5	Strongly more important
6	Strong to very strong more important
7	Very Strongly more important
8	Very to extremely strongly more important
9	Extremely more important

Step 3 *Check consistencies of experts' judgements*

The consistency ratio (CR) of the experts' judgements is evaluated for all the pair wise comparison matrices developed in Step 2. The normalized columns of entries of the pair wise comparison matrixare obtained by dividing each entry by the sum of column-wise entries. The principal vector (*PV*) is obtained by taking the averages of row wise entries. If the pair wise comparison matrices is denoted as M_1 and the PV as M_2, then $M_3 = M_1 \times M_2$ and $M_4 = M_3 / M_2$. If $\lambda_{\max}$ is the average of entries of M_4, then consistency index $CI = (\lambda_{\max} - N)/ N - 1$ where '*N*' is the number of attributes under consideration in the corresponding pair wise comparison matrix. Consistency Ratio, $CR = CI / RI$, where RI is the random consistency index corresponding to '*N*' (see

Table 6.3). Judgements are consistent if $CR \leq 0.1$. If not, revision of judgements is required to make sure that *CR* stays within the acceptable range.

Table 6.3: Random index (Saaty, 2001)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Step 4 *Convert the judgements into corresponding triangular fuzzy numbers*

Convert the experts' judgements in terms of triangular fuzzy numbers (TFNs) for all pair wise comparison matrices (see Table 6.4). The triangular fuzzy numbers corresponding to comparison of SA $'i'$ over enabler $'j'$' with respect to expert $'t'$ is denoted as $(P_{ijt}, \quad Q_{ijt}, \quad R_{ijt})$

Table 6.4: Outcome pair-wise comparison matrix of "EG 1"

	MP	FP	MA	PD	CS	BP	TP	SP
MP	1	0.5	1	0.5	0.333	1	1	0.333
FP	2	1	2	1	1	2	2	1
MA	1	0.5	1	0.5	0.333	1	1	0.333
PD	2	1	2	1	1	2	2	1
CS	3	1	3	1	1	2	2	1
BP	1	0.5	1	0.5	0.5	1	1	0.25
TP	1	0.5	1	0.5	0.5	1	1	0.25
SP	3	1	3	1	1	4	4	1

Consistency Ratio (CR) = 0.0083

Step 5 *Integrate the fuzzified pair wise comparison matrices*

The fuzzified pair wise comparison matrices obtained from Step 4 for each expert is integrated to obtain the integrated fuzzified pair wise comparison matrix. This integration is performed for both SAs and corresponding KPIs. The integration is performed by means of the geometric means method. The triangular fuzzy numbers corresponding to the comparison of enabler $'i'$ over enabler $'j'$' in the integrated pair wise comparison matrix are denoted as $(a_{ij}, \quad b_{ij}, \quad c_{ij})$ and they are calculated as follows:

$$a_{ij} = \left\{ \prod_{t=1}^{s} P_{ijt} \right\}^{\frac{1}{t}} \quad \forall i, j = 1,2,\ldots,n$$

$$b_{ij} = \left\{ \prod_{t=1}^{s} Q_{ijt} \right\}^{\frac{1}{t}} \quad \forall i, j = 1,2,\ldots,n$$

$$c_{ij} = \left\{ \prod_{t=1}^{s} R_{ijt} \right\}^{\frac{1}{t}} \quad \forall i, j = 1,2,\ldots,n$$

where'*s*' denotes the number of experts participating in the study

Step 6 *De-fuzzify integrated pair wise comparison matrices*

The integrated pair wise comparison matrices developed in step 5 should be de-fuzzified (according to the centroidal method, Kwong and Bai, 2003) and the consistency is again checked (Refer Step 3). If the consistency condition is satisfied, go to step 7, else, go to step 2.

$$d_{ij} = \frac{a_{ij} + 4b_{ij} + c_{ij}}{6}$$

Step 7 *Determine the fuzzy synthetic extent (FSE) of SAs and their KPIs*

The fuzzy synthetic extent of the SAs (Chang, 1996; Lee, 2009; Lee *et al.*, 2009a, b) and their corresponding KPIs are calculated according to the expression mentioned below:

$$F_i = \left(m_i^-, m_i, m_i^+\right) = \left\{ \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}}, \quad \frac{\sum_{j=1}^{n} b_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}}, \quad \frac{\sum_{j=1}^{n} c_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}} \right\} \quad \forall\, i = 1,2,\ldots,n$$

Step 8 *Determine degrees of possibilities* $\mu(F_i)$ *for each SA and corresponding KPIs*

FSE of each SAas calculated in Step 7 should be compared with the FSE of every other SA to determine the degree of possibilities $\mu(F_i)$ (Chang, 1996 and Zhu *et al.*, 1999).The degree of possibilities is calculated according to the expressions given below:

$$\mu\left(F_2 > F_1\right) = \begin{cases} 1, & m_2 \geq m_1 \\ 0, & m_1^- \geq m_2^+ \\ \dfrac{\left(m_1^- - m_2^+\right)}{\left(m_2 - m_2^+\right) - \left(m_1 - m_1^-\right)} & \text{otherwise} \end{cases}$$

Step 8 is repeated for the second level of the hierarchy.

Step 9 *Obtain the normalized weight for each SA and KPI*

The minimum of the degree of possibilities $\mu(F_i)$ for each attribute (either SA or KPI) is the weight obtained for the respective attribute. The weights are normalized by dividing the individual weight by the sum of the weights. This gives the normalized weights of each SA and the corresponding KPIs.

Step 10 *Obtain the priority weight of the KPI*

The priority weight of each KPI is obtained by multiplying the normalized weight of the respective KPI with their corresponding SA normalized weight.This forms the input to the PVA algorithm and it is discussed in Section 6.3.1.2.

6.3.1.2 Development of PVA to analyses the performance of the AM

One can find the applications of PVA for decision making in different areas of manufacturing. Some of recent applications of PVA include justification of world class manufacturing systems (Kodali *et al*., 2004); selection of facilities location (Kodali and Routroy, 2006); justification of green manufacturing systems (Sangwan, 2006); internal benchmarking for assessment of supply chain performance (Soni and Kodali, 2010);analyzing the performance of supplier development (Routroy and Pradhan, 2014); and performance analysis of agile supply chain (Routroy and Shankar, 2015).The detailed step-by-step procedure for implementing PVA is mentioned below:

Step 1 *Identify the time horizons*

The time horizon should be identified the s at which the performance of the AM needs to be evaluated. The time horizon is denoted as $a_i(i = 1,2,\ldots,I)$.

Step 2 *Classify the KPIs into direct and indirect categories*

The KPIs identified are classified as belonging to either direct category or indirect category. The direct category contains KPIs in which the performance grows as the measure increases. The indirect category contains KPIs where the performance decreases as the measure increases. The KPIs are denoted as $c_j(j = 1,2,\ldots,J)$.

Step 3 *Form the performance matrix*

The performance of each KPI with respect to each time horizon should be captured on the basis of experts' judgement. Therefore, the performance co-efficient d_{ijt} is obtained with respect to the performance of KPI (c_j) at the time horizon (a_i) for expert 't'. The performance of the KPI can be qualitative or quantitative.

Step 4 *Quantify the qualitative performance data*

The qualitative data that was mentioned in Step 3 is quantified using the 1-10 scale. 1 means very low, 3 means low, 5 refers to medium, 7 refers to high, 9 means very high, while 10 denotes excellent. The quantified performance data corresponding to KPI (c_j) at the time horizon (a_i) for expert 't'is denoted as x_{ijt}.

Step 5 *Obtain the average qualitative performance data*

The steps 3 and 4 are repeated for each expert. Then the average qualitative performance data (e_{ijt}) for each KPI is obtained according to the expression mentioned below:

$$e_{ijt} = \frac{\sum_{t=1}^{s} x_{ijt}}{s} \quad \forall\, i = 1,2,\ldots,I \text{ and } j = 1,2,\ldots,J$$

where 's' denotes the total number of experts

Step 6 *Obtain the normalized performance matrix*

The normalized performance co-efficient p_{ij} for each c_j corresponding to a_i is obtained as mentioned below.

- If the KPI belongs to the direct category, then $p_{ij} = \dfrac{e_{ij}}{\max\,(e_{ij})}$
- If the KPI belongs to the indirect category, then $p_{ij} = \dfrac{\min\,(e_j)}{e_{ij}}$

Step 7 *Obtain the priority weights of the KPIs*

The priority weight of KPI is calculated from the Fuzzy AHP process described in Section 4.1. The priority weight of KPI 'j' is denoted as W_j. The priority weights of the KPIs are entered in a separate column in the normalized performance matrix obtained from step 6.

Step 8 *Obtain the partial performance measure of the KPIs*

The partial performance measure of KPIs (Z_{ij}) corresponding to the performance of the enabler $'j'$ at time horizon $'i'$ is obtained by the multiplication of the normalized performance measure p_{ij} and the priority weight of the KPI as W_j

$$Z_{ij} = p_{ij} \times W_j$$

Step 9 *Obtain the aggregated performance of the KPIs at each time horizon*

The aggregated performance of the KPIs (also known as the desirable performance index) at each time horizon is calculated according to the expression mentioned below. This is used to analyse the performance of the AM at each time horizon.

$$N_i = \sum_{j=1}^{J} Z_{ij} \quad \forall\, i = 1,2,\ldots,I$$

6.3.2 Application of Proposed Methodology to an Indian Automotive Component Manufacturing Company

To remain competitive in fierce global competition, the Indian automotive component industry needs to have paradigm shift in their thinking to improve its production capabilities, productivity, quality and scalability (Jadhav *et al*., 2015). Therefore, many companies have implemented the right and appropriate manufacturing strategies to satisfy the needs of both Indian and global market. In India, many auto component manufacturers (i.e. Sundram Fasteners, Caterpillar, Brakes India, Bharat Forge, Gabriel India, Sona Koyo Steering Systems, Lakshmi Precision Screws Limited and many more) have developed the capability to supply components to automobile ‘Original Equipment Manufacturers (OEMs)’ both in India and aboard. Therefore, many multi-national companies have either established their businesses in India or are planning to do so (Singh *et al.,* 2007). The proposed methodology detailed in the previous section was applied to an automotive component manufacturing company located in the western part of India. The name of the case company is not disclosed in the current discussion due to non-disclosure agreement and from now on, it is referred as company ‘Z’. It manufactures automotive components related to the transmission systems for automotive manufacturing company. Its clients are both in India and aboard but major business comes from Indian market. It is known in the market for its agility, quality and reliability. The company ‘Z’ is an ISO certified company having proximity to its major supplier base. It has an in house research development centre and has also been receiving support from Original Equipment Manufacturers (OEMs) to develop its capability. It has also strong information infrastructure to enhance information visibility and coordination both with OEMs and major suppliers.

Five expert groups were formed with each group comprising of three experts. These experts are drawn from purchasing, manufacturing, quality control, logistics, marketing, and research and development department. The objectives of the study, proposed methodology and performance outcomes of AM along KPIs corresponding to each SA were clearly explained to the expert groups. The list of identified SAs along with their corresponding KPIs (as mentioned in Table 6.1) was discussed and was found to be relevant. Then pair wise comparison matrices for comparing the SAs and also their corresponding KPIs were presented to the five groups independently. Since there are eight SAs and each SA has its corresponding KPIs, a total of nine pair wise comparison matrices were obtained from each group. These pair wise comparison matrices were analyzed using FAHP to calculate the normalized weight of each KPI. Then, the KPIs were categorized (i.e. direct or indirect) and the desired performance of each KPI was fixed taking inputs from experts. The performance of each KPI across three time horizons (i.e. current, after six month and after one year) was captured on the basis of expert groups' judgements. The desired performance and performance across three time horizons of KPIs were taken in consensus for five expert groups. These performance values and normalized weights of KPIs were analyzed using PVA.

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6.3.3 Results and Discussions

Experts' judgements regarding the SAs and their corresponding KPIs in the form of pair wise comparison matrices for the company "Z" were obtained from each group of experts independently. The judgements were made according to the 1-9 scale as shown in Table 6.2. The pair wise comparison matrix of SA obtained from expert group one is shown in Table 6.4. In order to check the consistency of the input data, the consistency ratio was calculated and it was 0.0083, which is less than 0.1. Therefore, the judgements obtained from expert group one regarding the pair wise comparison of SA is consistent. Summarily, the pair wise comparison matrix of SA was developed by each expert group and its consistency was checked. Then, the crisp judgements corresponding to the pair wise comparison matrix of SAs were obtained from each expert group and were fuzzified (see Table 6.5). Table 6.6 shows the integrated fuzzified comparison matrices of SAs obtained by combining the fuzzified comparison matrices of SAs from all the five expert groups. The integrated fuzzified pair wise comparison matrices of SAs were then de-fuzzified to provide the de-fuzzified integrated pair wise comparison matrix of SAs as shown in Table 6.7. The consistency ratio of the de-fuzzified pair wise comparison matrix was also calculated and it was found to be 0.0243. Since the value was less than 0.1, the de-fuzzified data was also considered to be consistent. Table 6.8 provides the fuzzy synthetic extent of the SAs and then the normalized weights of the SAs were obtained as mentioned in Table 6.9. These steps were repeated in a similar manner for the KPIs corresponding to each SA (Level 2 of the hierarchy). The normalized weight of the SAs and KPIs are tabulated in Table 6.10. The priority weights of the KPIs were also calculated by multiplying the normalized weights of the KPIs with the normalized weights of the corresponding SA (see Table 6.10). These priority weights of the KPIs formed the input to the PVA algorithm. The performance of these KPIs of the company "Z" at three different time periods (current, after six month and after one year) was obtained from expert groups in consensus and is shown in Table 6.11. The linguistic performance input data provided in Table 6.11 was then converted in numerical terms

(See Step 4 in the PVA algorithm) and then, the normalized performances of the KPIs were calculated at the three time periods. It is shown in Table 6.12. These normalized performance measures of each KPI at three time periods were then multiplied with the priority weights of the KPIs obtained from FAHP and the partial performances of the KPIs at the three defined time periods. Table 6.12 also provides the partial performance measures of the KPIs at the three different time periods along with the desirable performance index (DPI) of the ASC. Table 6.13 shows the performance of each SA as a percentage of the desirable performance of that SA at each time period.

Table 6.5: Fuzzified pair-wise comparison matrix of "EG 1"

MP	(1, 1, 1) (0.333, 0.5, 1) (1, 1, 2) (0.333, 0.5, 1) (0.25, 0.333, 0.5) (1, 1, 2) (1, 1, 2) (0.25, 0.333, 0.5)
FP	(1, 2, 3) (1, 1, 1) (1, 2, 3) (1, 1, 2) (1, 1, 2) (1, 2, 3) (1, 2, 3) (1, 1, 2)
MA	(0.5, 1, 1) (0.333, 0.5, 1) (1, 1, 1) (0.333, 0.5, 1) (0.25, 0.333, 0.5) (1, 1, 2) (1, 1, 2) (0.25, 0.333, 0.5)
PD	(1, 2, 3) (0.5, 1, 1) (1, 2, 3) (1, 1, 1) (1, 1, 2) (1, 2, 3) (1, 2, 3) (1, 1, 2)
CS	(2, 3, 4) (0.5, 1, 1) (2, 3, 4) (0.5, 1, 1) (1, 1, 1) (1, 2, 3) (1, 2, 3) (1, 1, 2)
BP	(0.5, 1, 1) (0.333, 0.5, 1) (0.5, 1, 1) (0.333, 0.5, 1) (0.333, 0.5, 1) (1, 1, 1) (1, 1, 2) (0.2, 0.25, 0.333)
TP	(0.5, 1, 1) (0.333, 0.5, 1) (0.5, 1, 1) (0.333, 0.5, 1) (0.333, 0.5, 1) (0.5, 1, 1) (1, 1, 1) (0.2, 0.25, 0.333)
SP	(2, 3, 4) (0.5, 1, 1) (2, 3, 4) (0.5, 1, 1) (0.5, 1, 1) (3, 4, 5) (3, 4, 5) (1, 1, 1)

Table 6.6: Integrated fuzzified pair-wise matrix comparison of outcomes for five experts

MP	(1, 1, 1) (0.803, 0.871, 1.741) (0.608, 0.922, 1.552) (0.803, 0.871, 1.741) (0.461, 0.561, 1) (1, 1.32, 2.352) (0.608, 0.922, 1.552) (0.416, 0.644, 0.944)
FP	(0.574, 1.149, 1.246) (1, 1, 1) (0.608, 1.059, 1.683) (1, 1, 2) (0.608, 0.699, 1.32) (1, 1.516, 2.551) (0.608, 1.059, 1.683) (0.574, 0.85, 1.351)
MA	(0.644, 1.084, 1.644) (0.594, 0.944, 1.644) (1, 1, 1) (0.594, 0.944, 1.644) (0.441, 0.631, 0.871) (0.977, 1.303, 2.169) (1, 1, 2) (0.488, 0.668, 0.891)
PD	(0.574, 1.149, 1.246) (0.5, 1, 1) (0.608, 1.059, 1.683) (1, 1, 1) (0.549, 0.608, 1.059) (0.922, 1.431, 2.352) (0.608, 0.922, 1.552) (0.549, 0.803, 1.246)
CS	(1, 1.783, 2.169) (0.758, 1.431, 1.644) (1.149, 1.585, 2.268) (0.944, 1.644, 1.821) (1, 1, 1) (1.32, 2.352, 3.366) (0.922, 1.38, 2.048) (1, 1.32, 2.352)
BP	(0.425, 0.758, 1) (0.392, 0.66, 1) (0.461, 0.768, 1.024) (0.425, 0.699, 1.084) (0.297, 0.425, 0.758) (1, 1, 1) (0.525, 0.758, 1.149) (0.416, 0.488, 0.803)
TP	(0.644, 1.084, 1.644) (0.594, 0.944, 1.644) (0.5, 1, 1) (0.644, 1.084, 1.644) (0.488, 0.725, 1.084) (0.871, 1.32, 1.904) (1, 1, 1) (0.57, 0.725, 0.93)
SP	(1.059, 1.552, 2.402) (0.74, 1.176, 1.741) (1.122, 1.496, 2.048) (0.803, 1.246, 1.821) (0.425, 0.758, 1) (1.246, 2.048, 2.402) (1.076, 1.38, 1.755) (1, 1, 1)

Table 6.7: Integrated de-fuzzified pair-wise matrix comparison of outcomes for five experts

	MP	FP	MA	PD	CS	BP	TP	SP
MP	1	1.004	0.975	1.004	0.617	1.438	0.975	0.656
FP	1.069	1	1.088	1.167	0.787	1.602	1.088	0.888
MA	1.104	1.002	1	1.002	0.639	1.393	1.167	0.675
PD	1.069	0.917	1.088	1	0.674	1.5	0.975	0.834
CS	1.717	1.354	1.626	1.557	1	2.349	1.415	1.438
BP	0.743	0.672	0.759	0.717	0.459	1	0.784	0.529
TP	1.104	1.002	0.917	1.104	0.745	1.342	1	0.733
SP	1.611	1.198	1.526	1.268	0.743	1.973	1.392	1

Consistency ratio (CR) = 0.0243

Table 6.8: Integrated expert's judgment and fuzzy synthetic extent of outcomes

	$\sum_{j=1}^{n} b_{ij}^{-}$	$\sum_{j=1}^{n} b_{ij}$	$\sum_{j=1}^{n} b_{ij}^{+}$	m_i^{-}	m_i	m_i^{+}
MP	5.7	7.11	11.882	0.059	0.105	0.25
FP	5.974	8.332	12.833	0.061	0.123	0.27
MA	5.739	7.575	11.862	0.059	0.112	0.25
PD	5.312	7.972	11.138	0.055	0.118	0.234
CS	8.092	12.494	16.667	0.083	0.185	0.351
BP	3.942	5.556	7.818	0.041	0.082	0.164
TP	5.312	7.882	10.849	0.055	0.117	0.228
SP	7.471	10.655	14.169	0.077	0.158	0.298
Sum	47.54	67.575	97.217			

Table 6.9: Normalized weight of attributes

	DPA	MDPA	NWA
MP	(0.912, 0.965, 0.939, 0.677, 1, 0.945, 0.767)	0.677	0.116
FP	(1,1,1,0.752, 1,1,0.849)	0.752	0.129
MA	(1, 0.944, 0.971, 0.696, 1, 0.977, 0.791)	0.696	0.119
PD	(1, 0.97, 1, 0.693,1, 1, 0.799)	0.693	0.119
CS	(1,1,1,1,1,1,1)	1	0.172
BP	(0.821, 0.715, 0.779, 0.754, 0.442, 0.761, 0.537)	0.442	0.076
TP	(1, 0.962, 1, 0.992, 0.68, 1, 0.787)	0.68	0.117
SP	(1,1,1,1,0.888,1,1)	0.888	0.152

DPA: Degree of possibilities of attributes ; MDPA: Minimum of Degree of possibilities of attributes; NWA: Normalized Weight of attributes

Table 6.10: Priority weights of KPIs

OC	NWOC	KPI	NWKPI	RWKPI	OC	NWOC	NWOC	NWKPI	RWKPI
MP	0.116	CUS	0.255	0.03	CS	0.172	CRF	0.353	0.061
		MAC	0.249	0.029			CUD	0.263	0.045
		MCO	0.114	0.013			CUR	0.218	0.037
		MTI	0.167	0.019			CBE	0.165	0.028
		COT	0.104	0.012	BP	0.076	OPE	0.472	0.036
		PRE	0.111	0.013			OCE	0.237	0.018
FP	0.129	PRM	0.352	0.045			OCF	0.291	0.022
		PPEN	0.322	0.042	TP	0.117	SCA	0.048	0.006
		ECS	0.136	0.018			CPE	0.119	0.014
		ESU	0.19	0.025			LOL	0.051	0.006
MA	0.119	CME	0.139	0.017			ROP	0.009	0.001
		CMV	0.213	0.025			FIN	0.267	0.031
		IMS	0.148	0.018			EWT	0.175	0.02
		ENM	0.119	0.014			JSA	0.332	0.039
		RTC	0.166	0.02	SP	0.152	URE	0.185	0.028
		QRM	0.215	0.026			DRE	0.136	0.021
PD	0.119	PMA	0.305	0.036			ITR	0.131	0.02
		PRV	0.172	0.02			INF	0.132	0.02
		DNP	0.268	0.032			PIT	0.161	0.024
		PTR	0.079	0.009			RMC	0.127	0.019
		DEC	0.175	0.021			INV	0.128	0.019

OC: Outcome; NWOC: Normalized weight-age for outcome; NWKPI: Normalized weight-age for Key Performance Indicators; RWKPI: Relative weights for Key Performance Indicators

Table 6.11: Performance along KPIs for different time periods

Outcome	KPI	NKPI	PT 1	PT 2	PT 3	DP
MP	CUS	Direct	High	Very High	Very High	Excellent
	MAC	Direct	High	High	High	Excellent
	MCO	Indirect	Very High	Very High	High	Medium
	MTI	Indirect	High	Medium	Medium	Low
	COT	Indirect	High	Medium	Medium	Low
	PRE	Direct	Medium	Medium	High	Excellent
FP	PRM	Direct	Medium	Medium	High	Excellent
	PEN	Direct	Medium	Medium	Medium	Excellent
	ECS	Direct	Medium	Medium	Medium	Excellent
	ESU	Direct	High	High	High	Excellent

Outcome	KPI	NKPI	PT 1	PT 2	PT 3	DP
MA	CME	Direct	High	High	Very High	Excellent
	CMV	Direct	Medium	Medium	Medium	Very High
	IMS	Direct	Medium	Medium	High	Very High
	ENM	Direct	Low	Low	Medium	Very High
	RTC	Indirect	Medium	Low	Low	Very Low
	QRM	Direct	High	High	Very High	Excellent
PD	PMA	Direct	High	High	Very High	Excellent
	PRV	Direct	High	High	High	Excellent
	DNP	Direct	High	High	Very High	Excellent
	PTR	Direct	High	High	High	Excellent
	DEC	Direct	High	High	Very High	Excellent
CS	CRF	Direct	High	High	Very High	Excellent
	CUD	Direct	High	High	Very High	Excellent
	CUR	Direct	High	High	Very High	Excellent
	CBE	Direct	Medium	Medium	High	Excellent
BP	OPE	Direct	High	High	Very High	Excellent
	OCE	Direct	High	High	Very High	Excellent
	OCF	Direct	High	High	Very High	Excellent
TP	SCA	Direct	High	High	Very High	Excellent
	CPE	Direct	High	High	High	Excellent
	LOL	Direct	Medium	High	Very High	Excellent
	ROP	Direct	High	High	Very High	Excellent
	FIN	Direct	Medium	Medium	Very High	Excellent
	EWT	Direct	High	Very High	Excellent	Excellent
	JSA	Direct	High	High	Very High	Excellent
SP	URE	Direct	Very High	Very High	Very High	Excellent
	DRE	Direct	Medium	High	Very High	Excellent
	ITR	Direct	High	High	Very High	Excellent
	INF	Direct	Medium	Medium	Very High	Excellent
	PIT	Indirect	Medium	Medium	Low	Low
	RMC	Direct	High	Very High	Very High	Excellent
	INV	Direct	High	Very High	Very High	Excellent

NKPI: Nature of KPI; PT: Performance at time period;DP: Desired performance; PT 1: Performance at the current period;PT 2: Performance after six month; PT 3: Performance after one year

Table 6.12: Partial performance measures along KPI at different periods

KPI	NP T1	NP T2	NP T3	NDP	KPI	NP T1	NP T2	NP T3	NDP
CUS	0.021	0.027	0.027	0.03	CRF	0.0427	0.0427	0.0549	0.061
MAC	0.02	0.02	0.02	0.029	CUD	0.0315	0.0315	0.0405	0.045
MCO	0.007	0.007	0.009	0.013	CUR	0.0259	0.0259	0.0333	0.037
MTI	0.008	0.011	0.011	0.019	CBE	0.014	0.014	0.0196	0.028
COT	0.005	0.007	0.007	0.012	OPE	0.0252	0.0252	0.0324	0.036
PRE	0.007	0.007	0.009	0.013	OCE	0.0126	0.0126	0.0162	0.018
PRM	0.023	0.023	0.032	0.045	OCF	0.0154	0.0154	0.0198	0.022
PPEN	0.021	0.021	0.021	0.042	SCA	0.0042	0.0042	0.0054	0.006
ECS	0.009	0.009	0.009	0.018	CPE	0.0098	0.0098	0.0098	0.014
ESU	0.018	0.018	0.018	0.025	LOL	0.003	0.0042	0.0054	0.006
CME	0.012	0.012	0.015	0.017	ROP	0.0007	0.0007	0.0009	0.001
CMV	0.014	0.014	0.014	0.025	FIN	0.0155	0.0155	0.0279	0.031
IMS	0.01	0.01	0.014	0.018	EWT	0.014	0.018	0.02	0.02
ENM	0.005	0.005	0.008	0.014	JSA	0.0273	0.0273	0.0351	0.039
RTC	0.004	0.007	0.007	0.02	URE	0.0252	0.0252	0.0252	0.028
QRM	0.018	0.018	0.023	0.026	DRE	0.0105	0.0147	0.0189	0.021
PMA	0.0252	0.0252	0.0324	0.036	ITR	0.014	0.014	0.018	0.02
PRV	0.014	0.014	0.014	0.02	INF	0.01	0.01	0.018	0.02
DNP	0.0224	0.0224	0.0288	0.032	PIT	0.0144	0.0144	0.024	0.024
PTR	0.0063	0.0063	0.0063	0.009	RMC	0.0133	0.0171	0.0171	0.019
DEC	0.0147	0.0147	0.0189	0.021	INV	0.0133	0.0171	0.0171	0.019
PMA	0.0252	0.0252	0.0324	0.036	DPI	0.64	0.67	0.84	1

Table 6.13: Aggregated indices of outcomes at different periods

Time Period	Outcome							
	MP	FP	MA	PD	CS	BP	TP	SP
PT 1	0.589	0.538	0.522	0.7	0.667	0.7	0.637	0.667
PT 2	0.686	0.538	0.544	0.7	0.667	0.7	0.681	0.745
PT 3	0.727	0.608	0.675	0.85	0.867	0.9	0.893	0.916

6.3.4 Managerial Implications

The Desirable Performance Index (DPI) values obtained as the end result of the PVA algorithm represents the AM performance across the three identified time periods along the KPIs for the company "Z". The DPI for the current time period was calculated as 0.64. Similarly, the DPI value was found to be 0.67 and 0.84 after six month and after one year respectively. The performance of the SAs was also evaluated. The SAs were classified into three distinct categories on the basis of their performances namely, satisfactorily performing SAs, slightly underperforming SAs and severely underperforming SAs. The SAs with performance over or equal to 85% of the desired performance were considered to be satisfactorily performing; SAs with performances more than 75% and less than 85% of the desired performance were considered to be slightly underperforming and SAs with performance less than 75% of the desired performance were deemed to be severely underperforming. It was observed that the performance of all SAs in the current period and after six month fall in the severely underperforming category. However SAs namely CS, BP, TP, SP and PD fall in the category of satisfactorily performing SAs after one year. These SAs would achieve the desired performance in subsequent time periods and no corrective action was necessary. No SAs falling in the slightly underperforming category after one year. Finally, three SAs namely MP, FP and MA were classified under the severely underperforming category since they have 0.727, 0.608 and 0.675 of the desired performance respectively. It was suggested that the Failure Mode Effect Analysis (FMEA) should be performed on these SAs to determine the reasons for underperformance and appropriate action plans should be developed on the basis of these inputs. These SAs should be more frequently monitored to analyse the performance on a more real time basis.

6.4 Performance Analysis of Agile Manufacturing Enablers

In the 21st century, the manufacturing companies should understand, react and satisfy the ever increasing customer requirements (in terms of high quality and low cost product) to survive sustain and grow in the global business arena. Manufacturing companies those who are operating in relatively stable conditions with good market positions, are also facing rapid and often unanticipated changes in their business environment (Sharifi and Zhang, 2001). Only those organizations which are responsive to changes and are able to dynamically modify their processes and products to satisfy demands can excel in their business and make profits. Companies are restructuring and re-engineering themselves in response to the challenges and demands of the 21st century (Gunasekaran and Yusuf, 2002). AM is one of the operational strategies which organizations have adopted to beat environmental uncertainties resulting from worldwide economic recession, shortening of product life cycle, supplier constraints and obsolete technologies (Dubey and

Gunasekaran, 2015). AM is a new concept in manufacturing intended to improve the competitiveness of firms (Gunasekaran, 1999, Gunasekaran and Yusuf, 2002). The concept owes a lot to advances in communication technology and previous paradigms of manufacturing (Yusuf *et al.*, 1999). Therefore, it is obvious that AM requires huge investments along different areas in order to enhance the agility and its impact on business performance should be studied, monitored and evaluated along the timeline to justify such investments. Although one can find a lot of research in different dimensions of AM, but the performance analysis of AM along timeline is a new concept and is the requirement for the companies focusing on agility in their business environment. For the performance analysis of AM, the appropriate AMEs should be identified along with their corresponding Key Performance Indicators (KPIs) to enhance the AM implementation in the organizations. This study proposed an approach using GTA to identify the appropriate AMEs and to measure the performance of AM implementation along a specified time horizon.

6.4.1 Literature Review on Performance Analysis of Agile Manufacturing Enablers

AM is the capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services (Gunasekaran, 1998). A number of attempts have been made to define agility and AM. The main points of the definition of various authors may be summarized as follow: high quality and highly customised products (Goldman and Nagel, 1993; Kidd, 1995; Booth, 1995; and Hilton *et al.*, 1994), products and services with high information and value-adding content (Goldman and Nagel, 1993; and Goldman, 1995), mobilisation of core competencies (Goldman and Nagel, 1993; and Kidd, 1995), responsiveness to social and environmental issues (Goldman and Nagel, 1993; and Kidd, 1995), synthesis of diverse technologies (Burgess, 1994; and Kidd, 1995), response to change and uncertainty (Goldman and Nagel, 1993; Goldman, 1995; and Pandiarajan and Patun, 1994), and intra-enterprise and inter-enterprise integration (Vastag *et al.*, 1994; Kidd, 1995; and Youssef, 1992). AM requires enriching of the customer, co-operating with competitors, organizing to manage change, uncertainty and complexity, and leveraging people and information (Gunasekaran, 1999). Even though many manufacturing firms were still struggling to implement lean production concepts, AM is a vision of manufacturing that is a natural development from the original concept of `lean manufacturing'. In lean manufacturing, the emphasis is on the elimination of waste but AM is based on not only responsiveness and flexibility, but also the cost and quality of goods and services (Gunasekaran and Yusuf, 2002). Although the lean manufacturing approach has been considered in many past and present programs, analysis of the most recent programs shows a greater priority is given to the AM approach (Castro *et al.*, 2012). Adeleye and Yusuf, (2006) identified the competition and revealed significant differences in performance outcomes of AM through statistical tests by administering a questionnaire survey to 600 companies. Cao and Dowlatshahi, (2005) have done an empirical study to explore the impact of the alignment between virtual enterprise (VE) and information technology (IT) on business performance in an AM setting using structural equation molding and found that both VE and IT had positive influences on business performance for all industries. So, there is a need of performance analysis of AM in the current scenario.

6.4.1.1 Agile manufacturing enablers and their key performance indicators

Performance measurement is a fundamental principle of management. The measurement of performance is important because it identifies current performance gaps (i.e. current and desired performance) and provides indication of progress towards closing the gaps. Carefully selected key performance indicators identify precisely where to take action for improving performance (Weber and Thomas, 2005). In this paper AMEs and their KPIs are identified from literature review and expert's suggestion and are listed in Table 6.14.

Adaptability (*ADP*): It refers to the readiness and willingness of the organization to adopt new methods of operating the manufacturing system and also continually change in response to the ever changing environments. According to Sarkis (2001) adaptability of manufacturing industry can be measured by total amount of investment require to implement new process or to modify the process according to change in demand and quickness with which personnel can learn the new process or methodology. In addition to this, available facility of equipment and their limitation to cope with change in market also affects the adaptability of organization. Katayama and Bannett (1999) referred mental and physical responsiveness of each personal to cope with change and work effectively as a measure of adaptability, whereas Sherehiy *et al.* (2007) considers quickness to adjust with each individual or group for new task is a measure of adaptability along with ability of change with working culture. Engelhardt (2012) considered different approaches like modularity of existing process to change according to requirement, willingness to take new challenges and readiness to grasp the opportunity instantly and making decision for the same as performance indicator of adaptability that leads to agility. On the other side, level of transportation facility available for raw material and personnel delivery as per requirement of time is also taken as a performance measure for this enabler (Motadel *et al.*, 2013).

Product and Process Automation (*PPA*): It describes the various technologies that might be used to automate the different functions that are routinely carried out by the manufacturing system. Adoption of such automation makes the system faster and thereby contributes to agile behaviour. Gunasekaran (1999) suggested that ability of available workforce to automate and operate the process for current product demand is a measure of PPA, which is further supported and extended by Vinodh *et al.* (2010) by considering importance given to develop the skill of personnel for automation as a KPI. Yusuf *et al.* (1999) incorporates the combination of diversified technology to make the product and process automation quick and easy, which depends on the cross-functional capability of various engineering department and capability to choose the best technology for product and process automation according to requirement (Gunasekaran,1999). Sanchez and Nagi (2001) identified that availability and capability of equipment (e.g. computers), and software require for automating the process as a measure which depends on financial and moral support from top management.

Supply Chain Integration (*SCI*): It refers to all supply chain partner's working towards a common supply chain goal instead of individual goals. This increases overall supply chain profit which translates to profit for all the supply chain members. Supply chain integration is all about both upstream and downstream integration. Many researchers have shown the ways to measure SCI. Flynn *et al.* (2010) observed that collaboration with various suppliers to meet required demand, proper strategy to tackle inconveniences and risk, adequate and effective inbound and outbound logistic with wide spread supplier and dealer network is a measure. Consistency and constancy of various departments' decision and thinking process to achieve organizational goal is considered as performance indicator (Venkatraman and Prescott, 1990; and Milgrom and Roberts, 1995). Other factors related to finance and relations such as accountability of stakeholders and shareholder's benefits in decision making (Chen and Paulraj, 2004), integration of different units of organization in terms of sequence of process and operations, integration with end customer to get proper feedback (Stank *et al.*, 2001a), and knowledge sharing and helping culture between supplier of a company (Flynn *et al.*, 2010) considered as measure for SCI.

Core Competency (*CCT*): A core competency is not only something an organization does well but also a combination of capabilities that is unique, durable and extensive (Routroy, 2009). To be agile, it is necessary for firms to concentrate primarily on their core competencies and outsource or eliminate other activities. Kandampully (2002) presented a novel approach in which relation with the experts and scholars of firm's business field and capability and responsiveness of research and development department to maintain the uniqueness and innovativeness with market change considering the customer satisfaction and cost was a taken as a measure for CCT. In addition to this, expertise of partner firm which supports the core-competency of firm (Gunasekaran, 1998) and adherence to ethical principles and responsibility while handling dynamic conditions (Kavic, 2002) are important to calculate the performance of CCT.

Supply Chain key Partner's alacrity (*SCP*): It refers to the readiness exhibited by the supply chain partners in response to the business environments. SCP is an important enabler because the supply chain partners are ready to respond to various changes and hence the parts/components/services can be procured in short time. Therefore, AM can be established. From literature review, the different measures of SCP are found to be, expectation that partners will not act in opportunistic manner even if there are short term incentives to do so and contribute significantly for long term good (Spekman *et al.*, 1998). High degree of support for development of flexibility, responsiveness, low cost low volume manufacturing and ready to take risk from supplier side are considered as measures for SCP (Hoyt and Huq, 2000). Barney and Hansen (1994) considered the fairness and transparency of stakeholder and shareholders in profit sharing is a measure of SCP. Many researchers had indicated the measures related to partnership relation and capability of partners. Kim *et al.* (2010) considered availability of procedures which resolve the conflicts with proper justice in a speedy way among partners and ability of partners to cope with change easily as performance indicator. Gallear *et al.* (2012) mentioned that degree of corporate responsibility of partner as responsibility in terms of internal awareness, measurement and feedback sharing of best practice which leads to agility.

Devolution of Authority (*DOA*): It refers to the process of delegating authority to the members of the organization. It also enhances independent decision-making which thereby translates to quick decision-making. Knowledge and training provided to work effectively in cross-functional team is one of the KPI identified for DOA. Scholz-reiter and Freitag (2007) accounted decentralized co-ordination of intelligent logistic, routing the object through logistic system by intelligent part themselves, level of queue length which indicates the local decision making capability among parallel and alternative workstation to reduce WIP are the measures directly related to DOA. From literature and experts' opinion, it is noted that work and authority for each and every one to take quick and correct decisions with change in organization can also be an important consideration.

Information Visibility and Transparency (*IVT*): It refers to the seamless availability of accurate information across all levels of the organization. Information is critical to an AM environment to gauge the behavior of the market and the customers. Zhou and Benton (2007) proposed information sharing technology for continuous upgradation of operational data and the current status of demand and inventory which makes the decision quick and correct. It can be considered as an important indicator for IVT. In addition to this, good coordination among different departments helps in quick information flow and managing dynamic changes. Hibbard *et al.* (2001) proposed four dimensions (i.e. trust, commitment, co-ordination and joint problem solving) for measuring performance of IVT.

Manufacturing Management (*MFM*): It is related to conversion process which is core to many manufacturing organization. It includes the set of strategies that provide the foundation for effective manufacturing. For this enabler performance indicators are identified from literature review and discussion held with experts of Indian manufacturing companies during industrial visits. Amount of raw material yield, waste reduction ratio i.e. finished goods to raw material used, quick transfer of knowledge regarding men, machine and material with automatic data collection, level of measuring different manufacturing related matrices and converting them to financials, and degree of standardization of process are important measures for MFM.

Customer Relationship Management (*CRM*): It refers to the practices used by the Organization to enhance their relationship with the customers so as to serve them better.

It needs understanding, analyzing and managing customer expectations and complaints effectively and efficiently. Many literatures have discussed about measuring the CRM based on offering of products like responsiveness towards the demand of the product by customers, rapidness with which firm is able to introduce new product before the competitors (Lin *et al.*, 2006), variety of products to cover different segments of market (Boyer and Leong, 1996; Zhang *et al.*, 2003), delivery of product on committed time and providing service instantly as and when required (Hallgren and Olhager, 2009). Zhao *et al.* (2008) considered the participation of customer views on business decisions is major KPI for CRM.

Supplier Relationship Management (*SRM*): It involves close relationships with the suppliers to understand and analyze their shortcomings with the aim to work together to resolve these shortcomings so that the supplier is able to deliver the right products at the right time which will in turn enhance the agility. Lee *et al.* (2001) considered the policy of purchase which creates the win-win situation for the firm and supplier to measure the performance of SRM. Participation of supplier in business decisions like product development is also an important measurement factor. Wenger (2011) suggested effective co-ordination between supplier, sharing of best practices, training and education to employee from supplier side for better understanding of firm's goal and policies as KPIs. Another important measure emerged from literature study is information sharing and knowledge sharing to mitigate various possible risk.

Human Resource Management (*HRM*): It includes activities and efforts undertaken by the manufacturing organization to engage, motivate and retain their employees which in turn reduces attrition. It positively influences the attitude of the workforce thereby leading to increased productivity and performance. It is an enabler which is directly related to human perception and is difficult to generalize and measure. Bonavia and Marin-Garcia (2011) identified assurance of job security among the personnel, fairness and transparency in payment and amount of employee attrition rate as a measure of HRM. In addition to this, level of training and education provided to upgrade knowledge of employees according to latest technology, motivate the work force by revenue sharing or providing extra bonus based on their work, quality of working environment and other refreshment activity like sports week and informal gatherings etc are also important measuring factor.

6.4.2 Performance Analysis of Agile Manufacturing Enablers

AM is seen as the winning strategy to be adopted by manufacturers strengthening themselves for dramatic performance enhancements to become national and international leaders in an increasingly competitive market of fast changing customer requirements (Yusuf *et al.*, 1999). Performance is concerned with what happened in the past or what is happening in the present instance and therefore it is observable and measurable (Hon, 2005). Performance measurement is indispensable to manufacturing enterprise. AM improves both operational and financial performance (by developing manufacturing strength) whereas the greatest impact is noted in market performance (Vazquez-Bustelo *et al.*, 2007). Whereas Inman *et al.* (2011) put their view as, AM has a direct positive relationship with the operational performance of the firm, that the operational performance of the firm has a direct positive relationship with the marketing performance of the firm and that the positive relationship between the operational performance of the firm and the financial performance of the firm is mediated by the marketing performance of the firm. The literature suggests that various researchers have studied various aspects of AM performance and applied different analytical tools to analyze it. Hallgren and Olhager (2009) compared the lean and AM performance outcomes and suggested that the major differences in performance outcomes are related to cost and flexibility such that lean manufacturing has a significant impact on cost performance (whereas AM has not), and that AM has a stronger relationship with volume as well as product mix flexibility than does lean manufacturing. Measuring the abilities that a company has to respond to the changes in its business environment must be associated with the degree of turbulence and changes in the business environment (Sharifi and Zhang, 2001).

6.4.2.1 Proposed methodology for performance analysis of agile manufacturing enablers

The proposed methodology uses Graph Theory (GT) approach for evaluating the AM implementation process by performance analysis of AMEs. By applying GT Approach (GTA) in the current, an AMEs implementation performance index is determined. GTA has the ability to capture the performances along the KPIs (i.e. inheritance of the factors) of AMEs and their interdependencies (i.e. their interactions) along the significant categories so that the performance of AM implementation program can be evaluated effectively. Many researchers have applied GTA in addressing various research problems and are cited in this section. Anand and Bikram (2012) applied graph theory and matrix method for the measurement of horizontal collaboration intensity in a supply chain in a semi-conductor industry by developing horizontal collaboration index (HCI). Darvish *et al.* (2009) introduced graph theory and matrix method for the selection of contractor using contractor ranking in construction procurement. Wagner and Neshat (2010) preferred graph theory for the assessment of vulnerability of supply chain. Here, graph theory and matrix approach was applied for quantifying and mitigation of supply chain vulnerability. In this research supply chain vulnerability index (SVCI) was found and compared for different situations. Rao and Padmanabhan (2006) have applied digraph and matrix method for selection, identification and comparison of the industrial robots. Graph theory was used to find the robot selection index (RSI) based on selection attributes of industrial robots. Wani and Gandhi (1999) applied graph theory and matrix approach for evaluating the maintainability of a mechanical system by development of the maintainability index on the basis of maintainability attributes. Kulkarni (2005) applied graph theory and matrix approach for evaluating the performance of TQM in the Indian industries by developing TQM performance index that was used for evaluating and comparing various Indian companies practicing TQM. Aravind *et al.* (2013) focused towards the application of graph theory for conceptual modelling of the agile system and to compute the dependencies among the individual agile enabler, criteria and attributes as a top-down approach. The various applications of graph theory with the description and authors are tabulated in Table 6.15.

The procedural step to be followed in this work is mentioned below:

Step 1 Develop a Cross Functional Team (CFT) and the members should be preferably from supply, manufacturing, marketing and finance department. Each expert should have sound knowledge and experience about agility and AM. Collect the necessary responses from the CFT in this process.

Step 2 Identify the enablers and their KPIs. Classify them in to Significant Categories (SCs) and share these lists of KPIs under each AME with the team of experts formed in the previous step. The SCs can again be grouped according to their broad nature.

Step 3 Develop the diagraphs of all the groups, SCs and their corresponding KPIs as nodes. Position the SCs at the top level and their corresponding KPIs at the bottom level. Then conceptually join these nodes with the edges.

Step 4 The edges joining two nodes of the graph (unidirectional/ bidirectional) represent the interdependency between the SCs at the top level and between the KPIs of each SC at the bottom level.

Table 6.14: AMEs with their key performance indicators

Significant Categories (SCs)	Agile Manufacturing Enablers	Key Performance Indicators	Citations
Core Areas	Adaptability (ADP)	Cost to relocate process (CRP) Ability of learning new things (ALT) Current equipment facilities (CEF) Flexibility of human operator (FHO) Interpersonal adaptability (IAD) Cultural adaptability (CAD) Responsiveness to work stress (RWS) Flexibility of current process (FCP) Level of risk taking attitude (LRA) Responsiveness towards quick decision (RQD) Level of logistic flexibility (LLF)	Sarkis (2001); Katayama and Bannet (1999); Sherehiy*et a*l. (2007); Engelhardt (2012); Motadel *et al.* (2011) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.
	Product and process automation (PPA)	Level of knowledge of workforce (LKW) Degree of synthesis of diverse technologies (DDT) Degree of concurrency (DOC) Ability to select adequate technology (AAT) Financial capability (FIC) Level of infrastructure of hardware and software (LHS) Level of top management support and commitment (LTC) Degree of emphasis on skill development practices (DAM)	Gunasekaran (1999); Yusuf *et al.* (1999); Sanchez and Nagi (2001); Vinodth *et al.* (2010) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.
	Core competency (CCP)	Degree of relevance to customer (DRC) Level of scholarly relations (LSR) Capability of research and development (CRD) Level of information technology (LIT) Core competency of partner firm (CCP)	Hamel and Prahalad (1990); Kandampuly (2002); Lu and Ramamurthy (2011); Gunasekaran (1998); Kavic (2002) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.

Significant Categories (SCs)	Agile Manufacturing Enablers	Key Performance Indicators	Citations
		Breadth of target market segment (BMS) Degree of professionalism (DPR)	
	Devolution of authority (DOA)	Level of cross-functionality knowledge (LCK) Intelligence of logistic routing (ILR) Level of queue length (LQL) Quickness in response (QUR) Degree of clarity of responsibility among personnel (DCP)	Scholz-reiter and Freitag (2007); Mehrsri*et al.* (2014) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.
Management Practices	Human resource management (HRM)	Level of employment security (LES) Fairness of payment policy (FPP) Less employee turnover (LMP) Degree of education and training to employees (DTE) Level of practice for performance appraisal (LPA) Level of working environment condition (LEA)	Bonavia and Marin-Garcia (2011) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.
	Manufacturing management (MFM)	Availability of overall equipment effectiveness (AOE) Amount of raw material yield and waste reduction (ARM) Degree of knowledge transfer (DKT) Performance level (PLE) Degree of standardization of process (DSP)	Through discussion held with experts in an Indian automobile manufacturing company during industrial visits.
	Customer relationship management (CRM)	Degree of inclination to customer driven product (DCP) Quickness of introduction of new product (QNP) Level of product mix flexibility (LMF) Speed of delivery and service (AMS) Degree of customer integration (DCI)	Lin et al. (2006); Boyer and Leong (1996); Zhang *et al.* (2003); Hallgren and Olhager (2009); Zhao *et al.* (2008) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.
	Supplier relation management (SRM)	Level of benefits in purchase (LBP) Degree of supplier integration (DSI) Level of supplier alliance and sharing of best practices	Lee et al. (2001); Wanger (2011) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.

Significant Categories (SCs)	Agile Manufacturing Enablers	Key Performance Indicators	Citations
		(LAP) Training and education to employee from supplier side (TES) Negotiation and risk managing capability (NRC)	
Information Accessibility	Information visibility and transparency (IVT)	Degree of virtual integration (DRI) Visibility of inventory and real time demand data (VID) Degree of co-ordination among different departments (DCD) Level of relational governance (LRG)	Zhou and Benton (2007); Hibbard *et al.* (2001)and discussion held with experts in an Indian automobile manufacturing company during industrial visits.
	Supply chain integration (SCI)	Level of strategic collaboration (LSC) Capability and capacity of inbound and outbound logistic (CCL) Level of consistency among the structural characteristics (LSO) Degree of financial benefits (DFB) Level of internal and customer integration (LCI) Degree of supplier integration (DSI)	Flynn et al. (2010); Drazin*et al.* (1985); Venkatraman and Prescott (1990); Milgroms and Roberts (1995); Chen and Paulraj (2004a); Stank *et al.* (2001b); Cousins and Menguc (2006) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.
	Supply chain key partner's alacrity (SCP)	Level of trust among partners (LTP) Collaborative relationship among partners (CRP) Fairness of incentive and revenue sharing policy (FRP) Quickness of conflict resolution techniques (QRT) Capability of partner (CAP) Degree of corporate responsibility of partners (DCR)	Spekman*et al.* (1998); Hoyt and Huq (2000); Hansen *et al.* (1994); Kim *et al.* (2010); Galleare*t al.* (2012) and discussion held with experts in an Indian automobile manufacturing company during industrial visits.

Table 6.15: Various application of graph theory

S.N.	Authors	Application of graph theory
1	Anand and Bikram, 2012	Applied graph theory and matrix method for the measurement of horizontal collaboration intensity in a supply chain in a semi-conductor industry.
2	Darvish et al. 2009	Applied graph theory and matrix method for the selection of contractor using contractor ranking in construction procurement.
3	Wagner and Neshat (2010)	Applied graph theory for the assessment of vulnerability of supply chain.
4	Rao and Padmanabhan (2006)	Applied diagraph and matrix method for selection, identification and comparison of the industrial robots.
5	Rao and Padmanabhan, (2007)	Applied graph theory and matrix approach for the selection of rapid prototyping process for suiting the end use of the produced product.
6	Sehgal *et al.* (2000)	Applied graph theory for finding the location of fault of tribo-mechanical systems where digraph was created for failure propagation network of tribo-mechanical systems for finding the fault location.
7	Wani and Gandhi (1999)	Applied graph theory and matrix approach for evaluating the maintainability of a mechanical system by development of the maintainability index on the basis of maintainability attributes
8	Huang *et al.* (2008)	Applied graph theory for the automatic recognition of CAD.
9	Kulkarni (2005)	Applied graph theory and matrix approach for evaluating the performance of TQM in the Indian industries.
10	Faisal *et al.* (2007)	Applied graph theory and matrix approach for quantifying the risk mitigation environment of supply chain.

Table 6.16: Scale to quantify the level of interdependency between the members at a same level

Qualitative measure of interdependency	Quantified value
Very strong	5
Strong	4
Medium	3
Weak	2
Very Weak	1

Step 5 Assign a weight $\mathbf{b_{ij}}$ (see Table 6.16) for the all directed edges between the graph nodes to quantify the level of interdependency between members at the same level.

Step 7 Develop a Variable Permanent Matrix (VPM) of each group and SCs in which all diagonal terms represent the performances of corresponding KPIs under the SC and non-diagonal terms represent the extent to which each KPI positively influences other KPI.

Step 8 Develop a VPM for AM implementation program in which all the diagonal terms are filled with the permanent values of VPMs of SCs. The non-diagonal elements of VPM for the AM implementation program are filled by the interdependencies between the SCs. Then, calculate the permanent value of VPM for AM implementation program. The aforesaid permanent value is nothing but a function of a matrix similar to that of a determinant. The permanent equation say Per(*B*) for any 4*4 matrix is defined mathematically as mentioned below:

$$\begin{aligned}\mathrm{Per}(B) = {} & B^1B^2B^3B^4 + b_{12}b_{21}B^3B^4 + b_{13}b_{31}B^2B^4 + b_{14}b_{41}B^2B^3 + b_{23}b_{32}B^1B^4 \\ & + b_{24}b_{42}B^1B^3 + b_{23}b_{32}B^1B^4 + b_{34}b_{43}B^1B^2 + b_{12}b_{23}b_{31}B^4 \\ & + b_{21}b_{32}b_{13}B^4 + b_{12}b_{24}b_{41}B^3 + b_{21}b_{42}b_{14}B^3 + b_{13}b_{34}b_{14}B^2 \\ & + b_{41}b_{43}b_{31}B^2 + b_{23}b_{34}b_{42}B^1 + b_{32}b_{43}b_{24}B^1 + b_{12}b_{21}b_{34}b_{43} \\ & + b_{13}b_{31}b_{24}b_{42} + b_{14}b_{41}b_{23}b_{32} + b_{12}b_{23}b_{34}b_{41} + b_{14}b_{43}b_{32}b_{21} \\ & + b_{13}b_{34}b_{42}b_{21} + b_{12}b_{24}b_{31} + b_{14}b_{42}b_{23}b_{31} + b_{13}b_{32}b_{24}b_{41}\end{aligned}$$

The matrix is defined as $B = \begin{pmatrix} B^1 & b_{12} & b_{13} & b_{14} \\ b_{21} & B^2 & b_{23} & b_{24} \\ b_{31} & b_{32} & B^3 & b_{33} \\ b_{41} & b_{42} & b_{43} & B^4 \end{pmatrix}$

Step 9 The permanent value of VPM for the AM implementation program (calculated in the previous step) is expressed as Agile Manufacturing Implementation Performance Index (AMIPI). Generally this value would be quite high therefore, $\log_{10}(\mathrm{AMIPI})$ is used to reduce the AMIPI into a smaller number called the crisp value of the AMIPI.

Step 10 Calculate the crisp values of AMIPI for different case situations.

Step 11 Compare the crisp values of AMIPI across different periods to establish a relationship between company's performances along the timeline.

Step 12 Plot a graph with timeline on X-axis and crisp values of AMIPI of the company on Y-axis along with the lines at AMIPIs obtained across various case situations to visualize the implementation performance of AM.

The next section presents a case study conducted in an Indian automobile manufacturing company to demonstrate the application process.

6.4.3 Application of the Proposed Methodology

The proposed methodology was applied to an Indian automobile manufacturing company for analyzing the AMEs. As per the company's policy, to protect its confidentiality, to maintain good relationship with the company and to conduct further research, name of the company is not disclosed and it is named as 'case company'. The case company is a large scale automobile manufacturer. The company has pioneered in operations with over 20 years of manufacturing expertise in developing the flexibility to cater to any volume demand from the customer. The company has its market share across different parts of the world and has been an active competitor. No matter what the intricacy levels of product manufacturing, the company has always found innovative ways and technologies to make or source the product. With a monthly demand of half a million plus vehicles, it became imperative for the company to have robust processes to support AM. The proposed approach was applied to evaluate the implementation performance of AM. In the beginning of the application process, a detailed discussion was carried out with the senior engineers and managers in order to find the relevant KPIs of the AMEs relevant to the case company. These are discussed below in a systematic manner.

6.4.3.1 Selection of AMEs and their KPIs

In order to assess the degree of improvement, it was decided to take the judgments from five experts (drawn from the case company) to evaluate the AM implementation program. After the discussion with senior engineer and managers of the company, eleven AMEs (listed in Table 6.14) were found to be relevant for the case company. KPIs were found for the selected AMEs to measure the performance of each AME through literature review, brainstorming, and experts' opinion.The AMEs were grouped in three category i.e. core areas, management practices and information accessibility according to their broad area of similarity. The observations for the AM implementation program were taken for three consecutive years i.e. 2013 to 2015.

6.4.3.2 Development of diagraphs and quantification of the interdependency

Among the AMEs and KPIs identified some of them are dependent on another within a main grouping, while some of them within one group are dependent on other KPIs in another group. This is a fundamental assumption for the proposed GTA. In order to establish the relationship between the AMEs and KPIs, the expert's team used their own experiences and expertise and developed the diagraphs. The degree of interdependency was measured on a scale of 1 to 5 (between the SCs at top level, between the AMEs of each SC at mid-level and between the KPIs of each AME at bottom level) through collective judgments of five experts. Higher the value indicates higher the degree of interdependency. For example, if the interdependency level of SC 'X' is quite high with SC 'Y', then a value of 5 may be assigned.

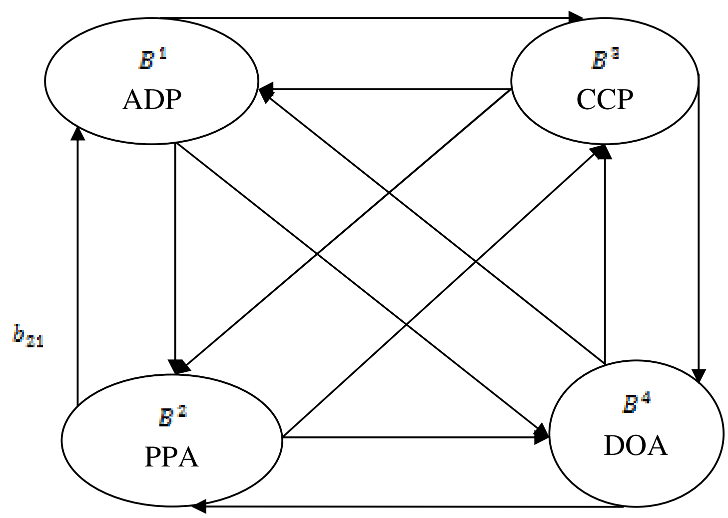

Figure 6.1: Interdependency levels between AMEs of significant category core areas

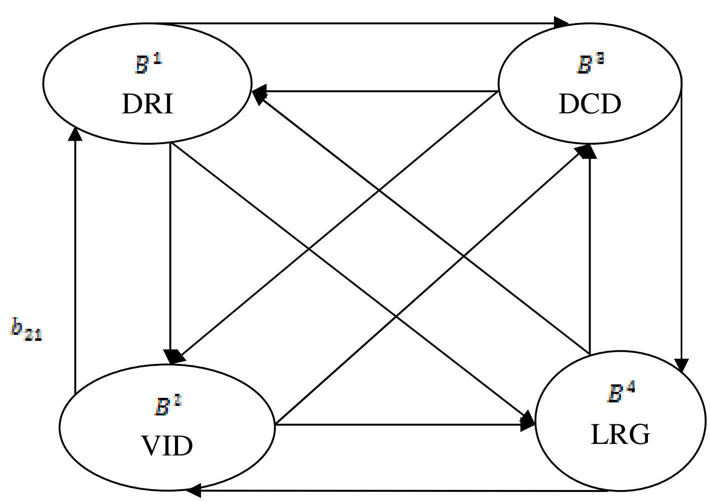

Figure 6.2: Interdependency levels of KPIs for AME 'IVT'

Figure 6.1 shows the interdependency that exists between the AMEs of SC ‘Core Areas’ whereas Figure 6.2 shows the interdependency that exists between the KPIs for the AME ‘IVT’. Similarly, the interdependency levels of other SCs are also obtained. A scale of 1 to 9 as shown in Table 6.17 was used to evaluate the performance of KPIs along 6 quarters (i.e. for three years). The diagonal elements of Table 6.18 show the performances of KPIs for the first quarter in the year 2013 and non-diagonal elements indicate the interdependency level of KPIs for the AME ‘IVT’.

6.4.3.3 Developing VPM

The problem was further solved through software that implements graph theoretic approach, developed in MATLAB R2013b on the basis of algorithm detailed in Figure 6.3. The PV of VPM of each SC and AME was calculated Table 6.19 shows the PVs of the SCs for the first quarter in the year 2013. Then the PV for the AM implementation program (i.e. AMIPI: Agile Manufacturing Implementation Performance Index) was calculated. This process was adopted for all the rest of five quarters. Table 6.20 shows the PVs and their corresponding AMIPI for all the twelve quarters from the year 2013 to 2015. As the AMIPI values were quite high, they were converted into logarithmic scale.

6.4.3.4 Scenario analysis

The degree of implementation and importance of various KPIs will result in different AMIPI. In order to calculate the range within which these values of AMIPI can vary, it is imperative to estimate the AMIPI for different situations (i.e. theoretically best, practically best, practically achievable, worst and ideal worst-case situation). One can find the similar approach used by the researchers (Grover *et al.*, 2005; Anand and Bahinipati, 2012).

Practically achievable case situation: In this case, a brain storming session was carried out in the case company to determine the performance that is feasible and achievable along different KPIs and AMEs. The interdependencies along KPIs with AMEs and AMEs with SCs (i.e. feasible) in the context of present and in the near future were considered. The VPM for KPIs under IVT is shown in Table 6.21, VPM for AMEs under “Information Accessibility” is shown in Table 6.22, and VPM for SCs for AM implementation is shown in Table 6.23. Finally AMIPI for this case was calculated and converted into logarithmic scale (see Table 6.24).

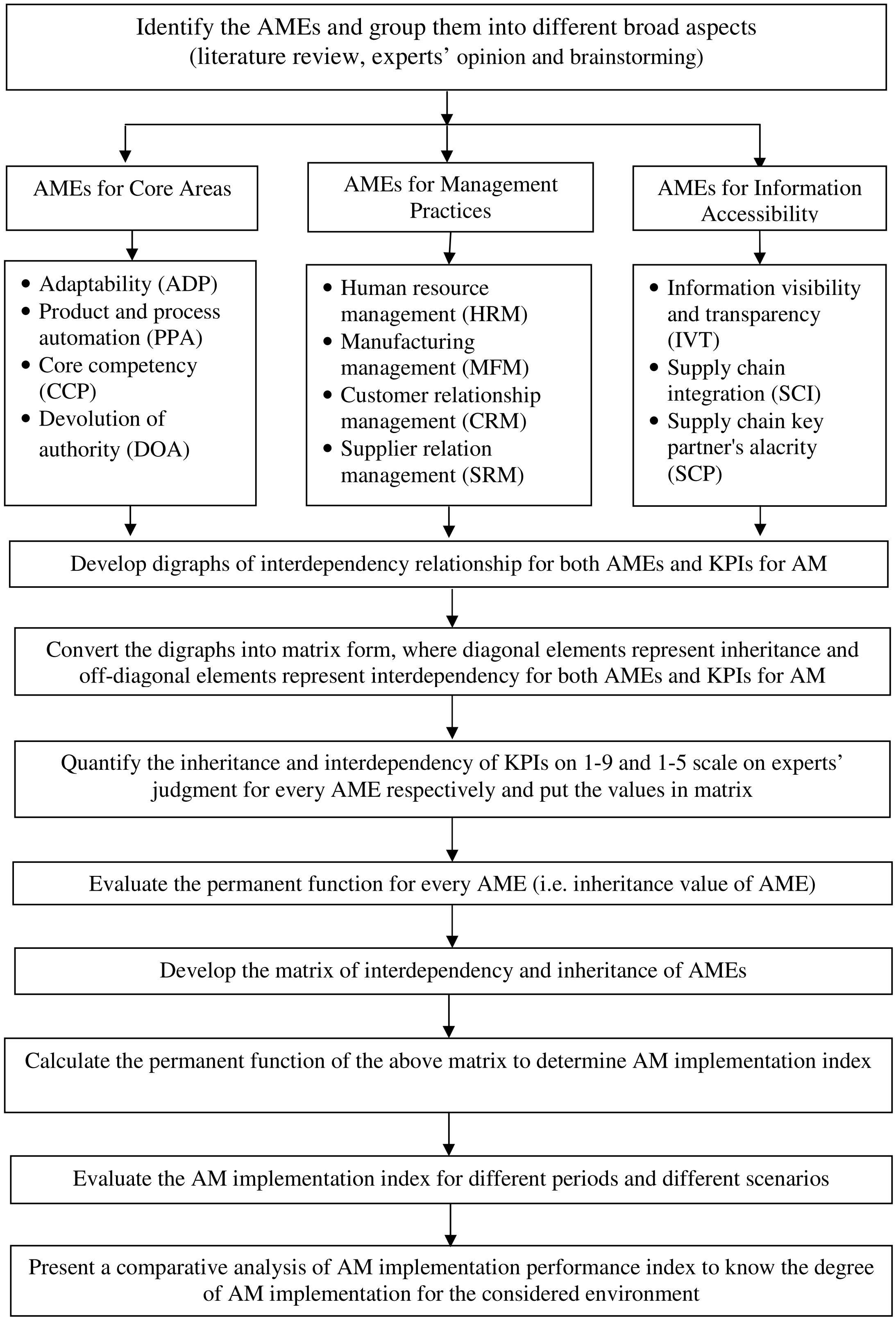

Figure 6.3: Flow chart of the proposed methodology for assessing the implementation performance of AM

Table 6.17: Scale for obtaining degree of performance (Saaty, 1980 and Satty, 2000)

Intensity of importance	Definition and Explanation
1	Extremely poor performance
2	Very poor performance
3	Poor performance
4	Marginally poor performance
5	Average performance
6	Marginally high performance
7	High performance
8	Very high performance
9	Extremely high performance

Table 6.18: Performance and interdependency levels of AME - 'IVT' in the first quarter, 2013

	DRI	VID	DCD	LRG
DRI	**5**	5	3	3
VID	4	**6**	4	2
DCD	3	2	**4**	2
LRG	1	2	3	**3**

Table 6.19: PVs of the SCs for the first quarter in the year 2013

SCs	Agile manufacturing enablers	PV of 2013 (1st Quarter)
Core Areas	Adaptability (ADP)	4.0056×10^{11}
	Product and process automation (PPA)	268084224
	Core competency (CCP)	10204300
	Devolution of authority (DOA)	34456
Management Practices	Human resource management (HRM)	339713
	Manufacturing management (MFM)	58566
	Customer relationship management (CRM)	31402
	Supplier relation management (SRM)	13856
Information Accessibility	Information visibility and transparency (IVT)	2454
	Supply chain integration (SCI)	452281
	Supply chain key partner's alacrity (SCP)	418417

Table 6.20: AMIPI for all the twelve quarters from the year 2013 to 2015

Year	Periods	PV of core areas	PV of management practices	PV of information accessibility	PV of SCs	AMIPI = Log_{10}(AMEs)
2013	1st Quarter	3.7756×10^{31}	8.6567×10^{18}	4.6440×10^{14}	1.5179×10^{65}	65.1812
	2nd Quarter	8.9043×10^{31}	3.3335×10^{19}	1.0688×10^{15}	3.1725×10^{66}	66.5014
2014	1st Quarter	2.3259×10^{32}	1.0204×10^{20}	2.1719×10^{15}	5.1547×10^{67}	67.7122
	2nd Quarter	5.3281×10^{32}	2.5513×10^{20}	4.3328×10^{15}	5.8898×10^{68}	68.7701
2015	1st Quarter	1.2080×10^{33}	5.1637×10^{20}	7.7276×10^{15}	4.8203×10^{69}	69.6831
	2nd Quarter	2.4678×10^{33}	1.1918×10^{21}	1.5251×10^{16}	4.4855×10^{70}	70.6518

Table 6.21: Performance and interdependency levels of KPIs under 'IVT' in practically achievable case situation

	DRI	VID	DCD	LRG
DRI	**9**	5	3	3
VID	4	**8**	4	2
DCD	3	2	**9**	2
LRG	1	2	3	**8**

Table 6.22: Performance and interdependency levels of AMEs under "Information Accessibility" for AM implementation in practically achievable case situation

	IVT	SCI	SCP
IVT	10756	3	4
SCI	3	1818708	3
SCP	4	5	1684646

Table 6.23: Performance and interdependency levels of SCs for AM implementation in practically achievable case situation

	Core areas	Management practices	Information accessibility
Core areas	5.4649×10^{33}	3	4
Management practices	2	3.0926×10^{21}	2
Information accessibility	2	3	3.2955×10^{16}

Table 6.24: PVs of VPMs of SCs and AMIPIs along different case situations

	PV of core areas	PV of management practices	PV of information accessibility	PV of AMEs	AMIPI= Log_{10}(AMEs)
PA	5.4649×10^{33}	3.0926×10^{21}	3.2955×10^{16}	5.5696×10^{71}	71.7458
TB	1.1118×10^{41}	1.4546×10^{25}	2.0896×10^{19}	3.3794×10^{85}	85.5288
PB	1.2400×10^{34}	6.5645×10^{21}	6.3033×10^{16}	5.1309×10^{72}	72.7102
TW	1.2170×10^{28}	1.0630×10^{16}	4.1981×10^{12}	5.4310×10^{56}	56.7349
IW	9.7340×10^{17}	1.2466×10^{9}	12460056	1.5120×10^{34}	34.1796

PA: Practically Achievable; TB: Theoretical Best; PB: Practically Best; TH: Theoretically Worst; IW: Ideal Worst

***Theoretically best case situation*:** The hypothetical best-case or theoretical best-case situation was derived by having the maximum values for both performances and interdependencies in the AM implementation program. Therefore, the diagonal elements of VPM of KPIs and AMEs for the three significant categories would be 9 and other elements of VPM would be 5. The performance value of each significant category as calculated above was taken as diagonal elements of VPM and non-diagonal elements as 5. Finally AMIPI for this case was calculated and converted into logarithmic scale (see Table 6.24).

***Practically best case situation*:** In this case, it was assumed that the performance of all KPIs and AMEs have reached to the highest level. Therefore, the diagonal elements of VPM of KPIs and AMEs for the three significant categories would be 9. The other elements of VPM would be as previously found out by the experts' opinions. The performance value of each significant category as calculated from above will become the diagonal element of VPM and non-diagonal elements will be as previously found out by the experts' opinions. Finally, AMIPI for this case was calculated and converted into logarithmic scale (see Table 6.24).

***Worst case situation*:** In this case, it was assumed that the performance and dependency level of all KPIs and AMEs is at minimum. Therefore, the diagonal elements of VPM of KPIs and AMEs for the three SCs would be 1 and the other elements of VPM will be as previously found out by the experts' opinions. The performance value of each significant category as calculated from above will become the diagonal element of VPM and non-diagonal elements will be as previously found out by the experts' opinion. The finally AMIPI for this case is calculated and converted into logarithmic scale (see Table 6.24).

***Ideal worst case situation*:** The hypothetical worst-case or theoretical worst-case situation can be derived by having the minimum values for both performances and interdependencies in the AM implementation program. Therefore, the diagonal elements of VPM of KPIs and AMEs for the three significant categories would be 1 and other elements of VPM would also be 1. The performance value of each significant category as calculated from above will become the diagonal element of VPM and non-diagonal element will be 1. Finally, AMIPI for this case is calculated and converted into logarithmic scale (see Table 6.24).

6.4.4 Results and Discussions

The main purpose of calculating the AMIPI for the case company is to determine the level of implementation of AM by comparing with the PA, TB, PB values along the timeline and this will also be helpful for the case company to benchmark its AM implementation with other similar company who have excelled in the implementation of AM or implementing AM. Here, for internal benchmarking the case company can use the Practically Best AMIPI value 72.7102 as its standard. The case company is now performing very well as compared to the Theoretically Worst AMIPI value 56.7349. The AMIPI values can be used as parameters for deciding the future vision and mission of the company to enhance the AM implementation program and it will act as a roadmap for the company.

The final permanent values of all significant categories depicts that the AMEs of 'Core Areas' have greater influence in AM implementation program followed by 'Management Practices' and 'Information Accessibility'. Among the AMEs of the core area, the KPIs of adaptability (ADP) have a greater influence than others. The permanent values of major AMEs help in determining the crisp score of AMIPI which is estimated to 70.6518 after the second quarter of 2015. For an ideal case of theoretically best case, all the AMEs and their KPIs equally contribute to the performance of the case company. The crisp score of AMIPI for an ideal case is estimated to be equal to 85.5288. The AMIPI value for the theoretically worst and ideal worst case situation was found to be 56.7349 and 34.1796 respectively.

The graph plotted between the implementation timeline in X-axis and the AMIPI values of all scenarios in Y-axis (Figure 6.4, 6.5, 6.6, and 6.7) indicates the trend it has been following. The performance of the case company has increased during three years due to the implementation of AM program and a more effort will make them to achieve their goal and stand as a market leader in AM implementation.

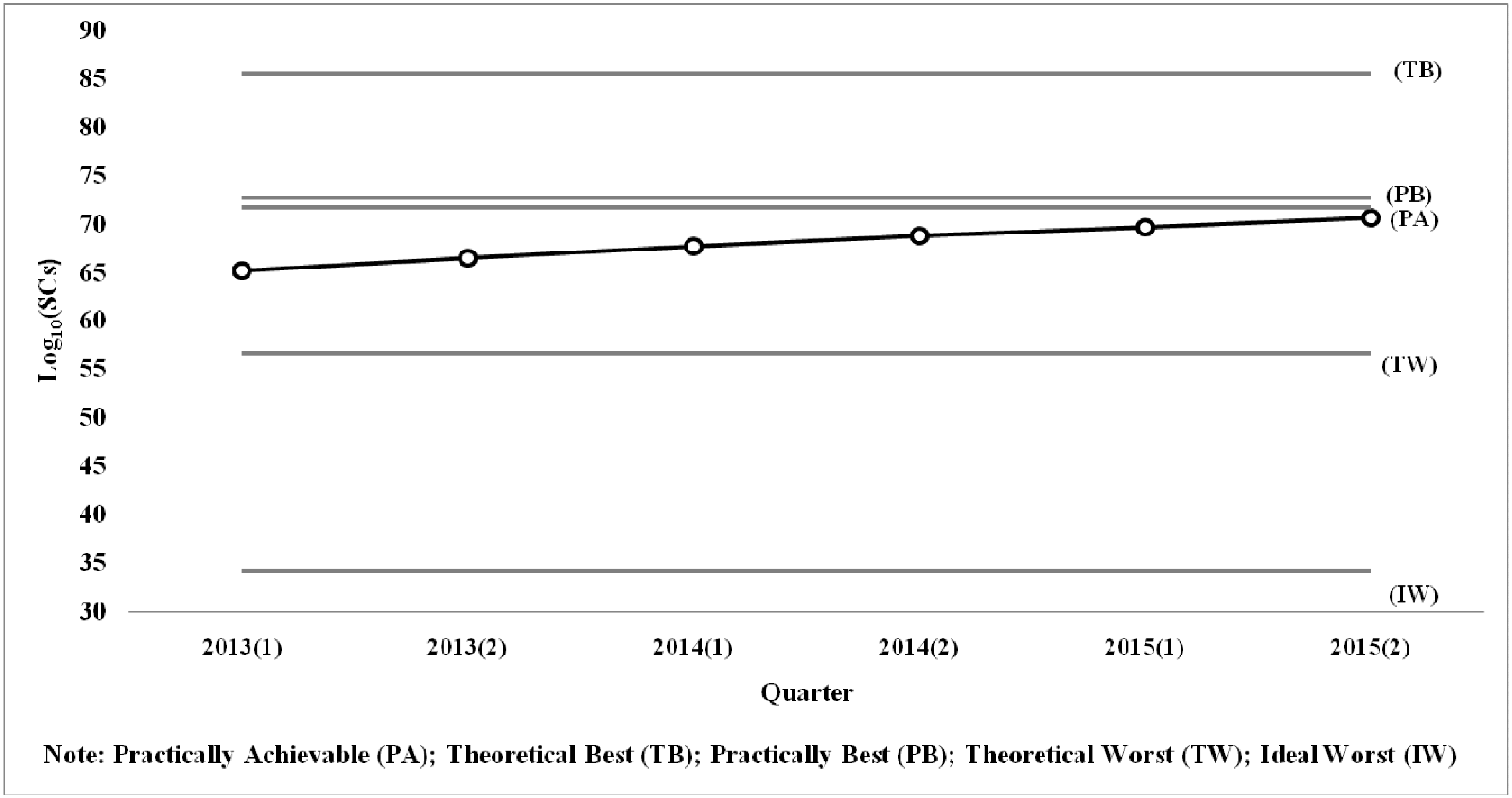

Figure 6.4: Agile manufacturing implementation performance along the time line

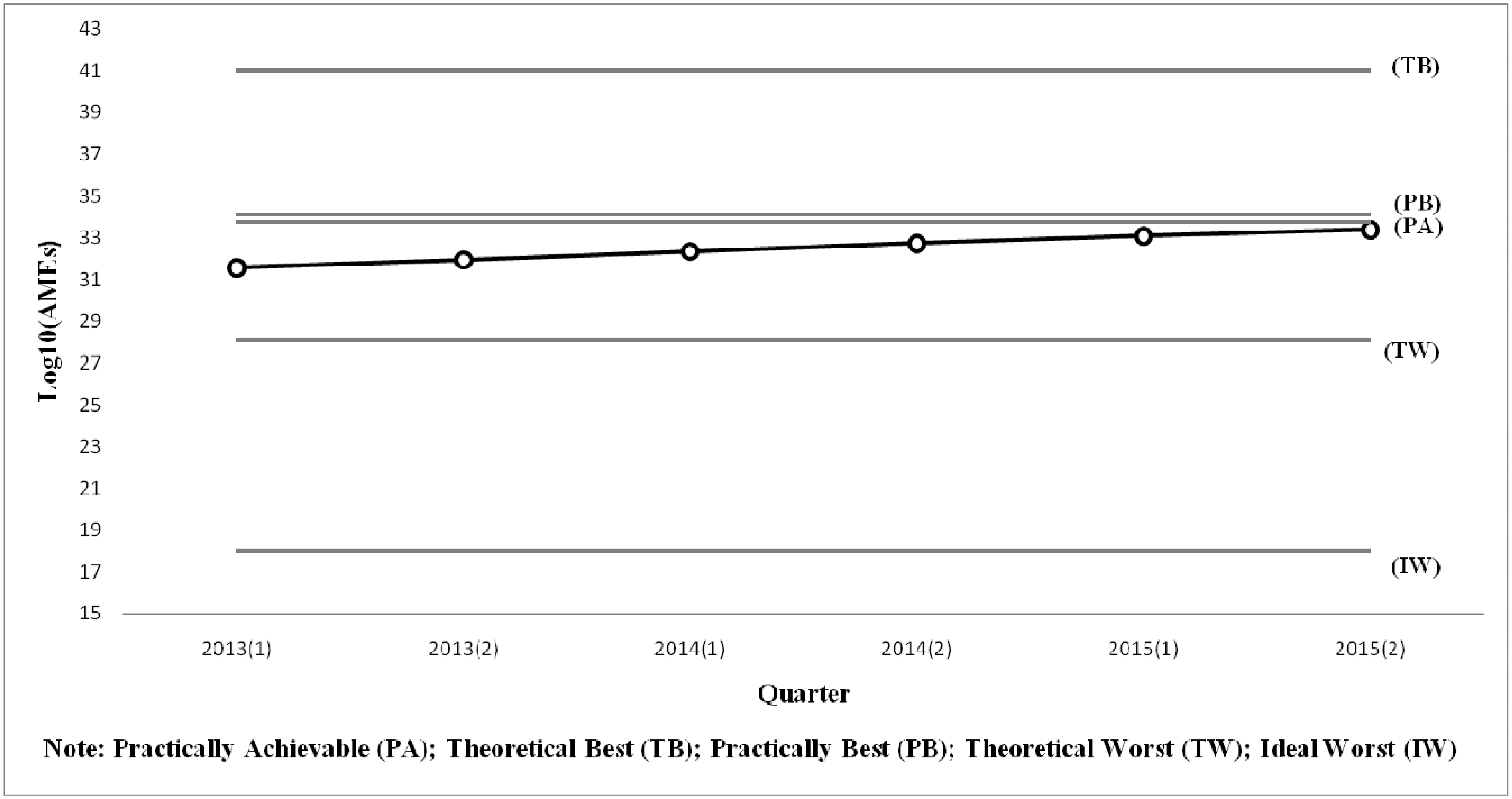

Figure 6.5: Agile manufacturing implementation performance along the time line for "core areas"

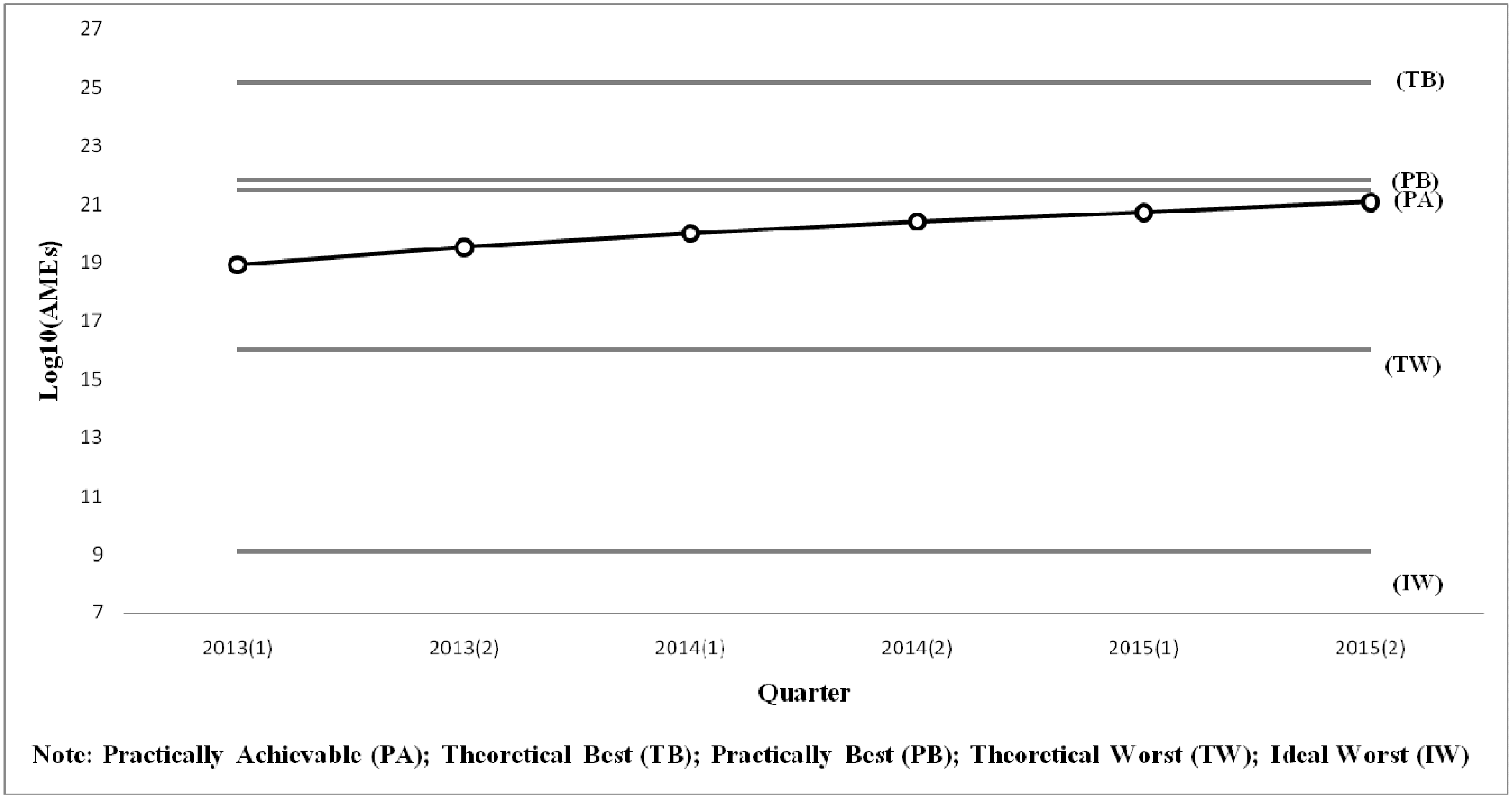

Figure 6.6: Agile manufacturing implementation performance along the time line for "management practices"

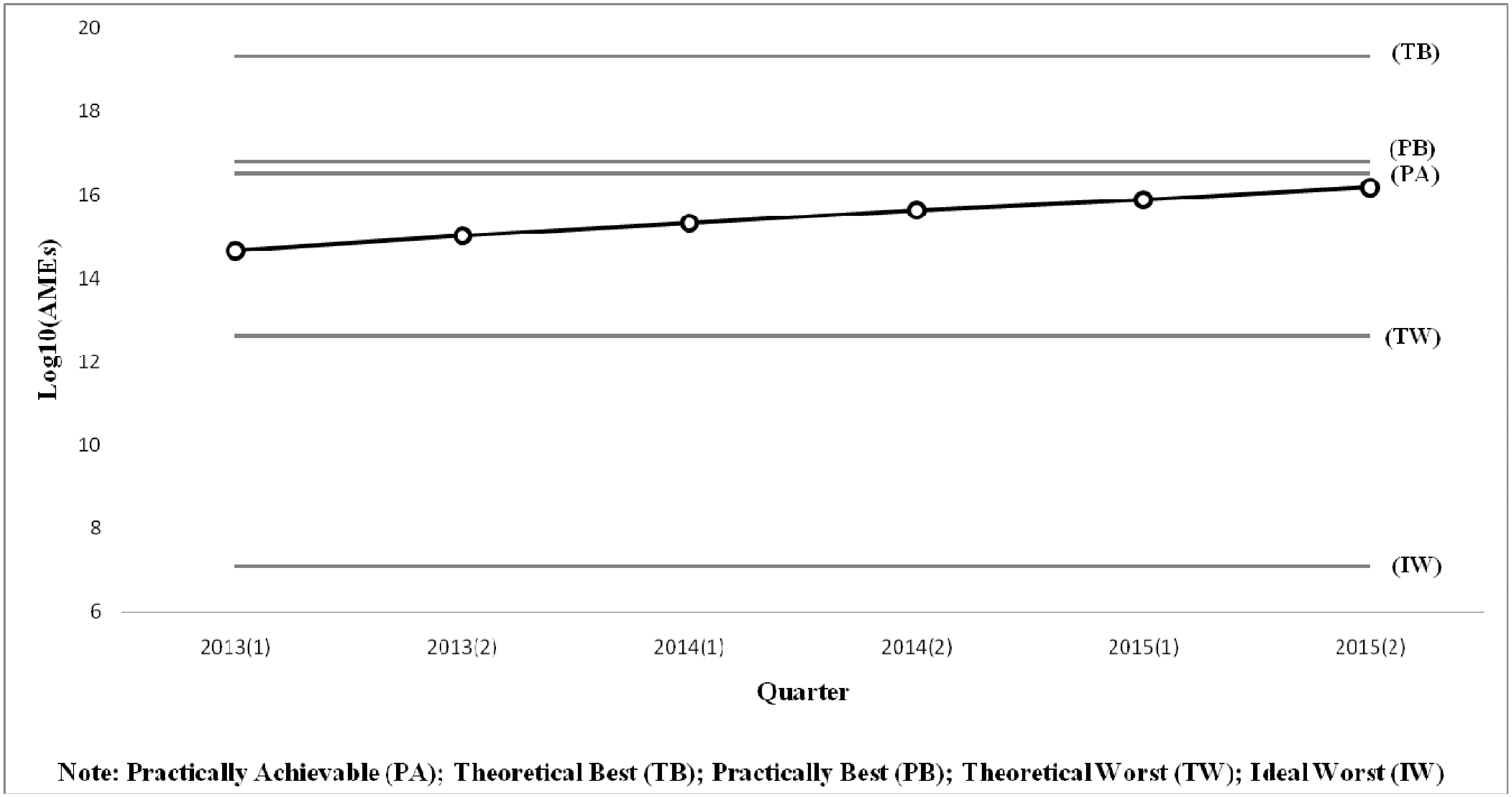

Figure 6.7: Agile manufacturing implementation performance along the time line for "information accessibility"

6.5 Conclusions

Performance measurement is the process of quantifying action, where measurement is the process of quantification and thereby needful action will lead to a better performance. In today's date, companies are facing lot of challenges from their competitors to remain as a market leader in terms of responsiveness to change in the market. However, measuring the implementation performance of AM is essential to direct the efforts and resources in a right direction. Two methodologies were developed for AM performance evaluation. The first methodology was developed based on AM outcomes and their corresponding KPIs for quantifying, analyzing and evaluating the performance along different timelines in a specific manufacturing environment and fills the gap that exists in the area of AM performance evaluation. The proposed AM performance evaluation methodology was applied to an Indian auto component manufacturer. The proposed methodology requires pair-wise comparisons for outcomes and their corresponding KPIs whereas pair-wise comparisons are not required for alternative analysis (i.e. current, after six month, after one year and desired environment). Due to this, only nine pair-wise comparisons matrices were made (i.e. one for outcomes and eight for their corresponding KPIs) in order to calculate the normalized weights of the KPIs for the case company. By the process, forty two pair-wise comparisons matrices for analyzing the four alternatives along the forty two KPIs were avoided. The priority weights of the KPIs were calculated considering multiple experts' judgements and their consistency in the judgements were also checked. It was concluded from the obtained results that the performance of the AM is improving but it has achieved 84% of the desired performance at the end of one year. However, it was observed that the AM performances along three outcomes (i.e. MP, FP and MA) were found to be underperforming even after one year. The continuous monitoring of Desired Performance Index values will help managers to track and monitor the AM performance without actually measuring AM agility which in turn will trigger for corrective actions on real time basis.

The second methodology was developed to quantify, evaluate and compare the implementation performance of Agile Manufacturing (AM) program using Graph Theoretic Approach (GTA) along Agile Manufacturing Enablers (AMEs). Broadly eleven Agile Manufacturing Enablers (AMEs) with their Key Performance Indicators (KPIs) were identified and they were classified into three Significant Categories (SCs). Featuring these SCs, AMEs and their KPIs, GTA was proposed. The analysis was further extended to evaluate the performance along the timeline and eventually compare the results with different performance scenarios to set the future targets. A case study of an Indian automobile manufacturing company was discussed in detail in order explain the salient features of the proposed approach and get an insights to the real life industry scenario. It was found that the performance of the case company was increased continuously and after three years, the performance of the company was enhanced to significant level compared to its performance at the beginning of the AM implementation program. This evaluation process has enabled the case company to follow up the trend line of the AM implementation process and capture the level of implementation in each quarter of the financial year. The numerical results obtained are completely in specific to the case company and they cannot be generalized for other companies. But, the proposed approach will be quite useful for the managers to measure the implementation performance of an AM program over a period of time and along various situations. The managerial implications of this work are mentioned below.

- The framework proposes a generic decision making model by taking the AMEs to measure the performance of a company.
- The outcomes of this framework provide an effective method to evaluate the level of AM implementation and where the company stands with respect to its goal.
- It also tracks the individual AMEs and their KPIs to determine the necessary improvements needed to each one.
- Training programs can be conducted for the employees on the particular topics where they are found to be lacking from the performance report.

GTA was used in the present study for evaluating the performance of a single organization. In future, this model can be implemented simultaneously in several similar organizations to determine its feasibility and the performance of the companies. This will be helpful to benchmark the implementation process. More generic results can be obtained using this process. To reflect the importance of an AME, the number of KPIs of that AME can be varied. The present model can also be implemented to measure the performance of the companies implementing lean manufacturing and le-agile manufacturing with proper selection of AMEs and their considering KPIs.

CHAPTER 7

A Benchmarking Approach for Enhancing Agility

7.1 Introduction

Manufacturing organizations are struggling to achieve and maintain the competitive advantage in today's turbulent business environment. Agility is the ability to be responsiveness to the changes in business environment and convert them into opportunities (Zhang and Sharifi, 2000). Therefore, agile concept is gaining importance in various sectors and is not restricted to manufacturing (Thilak *et al.*, 2015; Fayezi *et al.*, 2015; and Liu and Liang, 2015), software (Misraand Singh, 2015; Mandal and Pal, 2015; and Stettina and Hörz, 2015), healthcare (Tolf *et al.*, 2015) etc. Yusuf and Adeleye (2002) carried out a study taking inputs from manufacturing organizations in UK and found that the major lean attributes (i.e. cost and quality) have a limited relationship with business performance measures. They also empirically established that the agile organizations had better performance criteria in comparison with lean organizations and also concluded that lean organizations have to improve agility level for enhanced competitive advantage. Sangari and Razmi (2015) found from the empirical data (collected from automotive manufacturing companies in Iran) that the agile capabilities partially mediate the relationship between business intelligence competence and agile performance of the supply chain. The fierce competition and volatility in the current automotive market had forced automotive organization to focus both on cost and availability and had to adopt Agile Manufacturing (AM) to win orders in the market (Elmoselhy, 2015). Gligor *et al.* (2015) empirically confirmed that as the agility level of supply chain increases so does the firm's ability to effectively meet customers' requirements and a higher agility level of supply chain can help to achieve customer-related objectives regardless of the firm's operating environment. Shin *et al.* (2015) studied the connections between strategic agility of Korean small and medium enterprises (SMEs) and its underlying dimensions (technology capability, collaborative innovation, organizational learning, and internal alignment) using structural equation modeling. They found that strategic agility showed not only the direct effect but also the stronger indirect (mediation) effect through operational responsiveness on customer retention. Therefore, to sustain in long run, all organizations have to put efforts for enhancing the agility level. To become agile organization, AM is prerequisite in manufacturing environment. It is the competitive manufacturing paradigm enabling the mass customization efficiently coupled with high responsiveness to improve the performance of their businesses. In order to continually operate AM systems in difficult operating environments, it is important to measure and improve the agility of the corresponding manufacturing systems (Routroy *et al.,* 2015).

Although benchmarking approach is applied successfully in many areas and many research papers are reported in literature to improve the performance of the system, but not much literature is available on the application of benchmarking approach for AM for enhancing its agility performance. Hence, a complete and structured conceptual AM framework is developed based on benchmarking approach. The step by step implementation process of the proposed generic benchmarking framework is discussed in detail. This paper is organized as follows. The agility, agile manufacturing and some significant aspects related to AM (i.e. frameworks, enablers, impediments, outcomes and agility assessments, and benchmarking) is presented in Section 7.2 whereas the conceptual benchmarking framework for AM and its implementation procedure are presented in Section 7.3. Section 7.4 presents conclusions which include the managerial implications, limitations and future scope.

7.2 Literature Review

Some significant aspects related to benchmarking of agility for AM, that are reported in the literature are mentioned and discussed in detail.

7.2.1 Benchmarking

Benchmarking can be defined as a management tool that may be employed for attaining or exceeding the performance goals by learning from the best practices globally (Anand and Kodali, 2008). From a managerial perspective, benchmarking has been defined as a continuous, systematic process for evaluating the products, services, and work processes of organizations that are recognized as representing best practices for the purpose of organizational improvement (Sarkis, 2001). Benchmarking for agility can be defined as benchmarking within an agile environment or benchmarking agile programs (Sarkis, 2001).The concepts of agility, agile manufacturing and benchmarking are widely understood and developed independently, but combining all the three concepts simultaneously is relatively recent and needs to be developed. It is critical for firms to focus on benchmarking in transforming their operations in order to become agile (Underdown and Talluri, 2002).Therefore, the application of benchmarking in enhancing the agility of manufacturing organization in general and agile manufacturing in specific should be viewed as necessary rather than optional. Rigor in theory and practice will aid in dissemination of benchmarking for agility and reduce its organizational and investment risk (Sarkis, 2001).Only a few studies (Meredith and Francis, 2000; Sarkis, 2001; Hoek *et al.*, 2001; and Vinodh *et al.*, (2015)) have been reported in the literature on the application of the benchmarking approach for enhancing the agility. The process of benchmarking may need some adjustment for agile environments (Sarkis, 2001). Although the research contributions made in these studies are valuable, the systematic procedure of benchmarking approach for agility would be an addition to the existing knowledge base. Therefore, a conceptual benchmarking framework of AM for enhancing agility is proposed and detail discussion is carried out in the following section.

7.3 Conceptual Benchmarking Framework of AM for Enhancing Agility

A conceptual benchmarking framework of AM for enhancing agility is proposed (see Figure 7.1). It consists of nine phases (cross functional team formation; identification of the enablers, barriers and outcomes; analysis of enablers and barriers for selection; identification of benchmarking partners for selected barriers and enablers; gap analysis; development of strategies on the basis of gap analysis; implementation of proposed strategies; monitoring the performance through the selected outcomes; and continuous improvement)and each phase has number of steps (see Section 7.3.2). The total number of steps for all the phases is 38 and each stage is discussed (see Section 7.3.2).

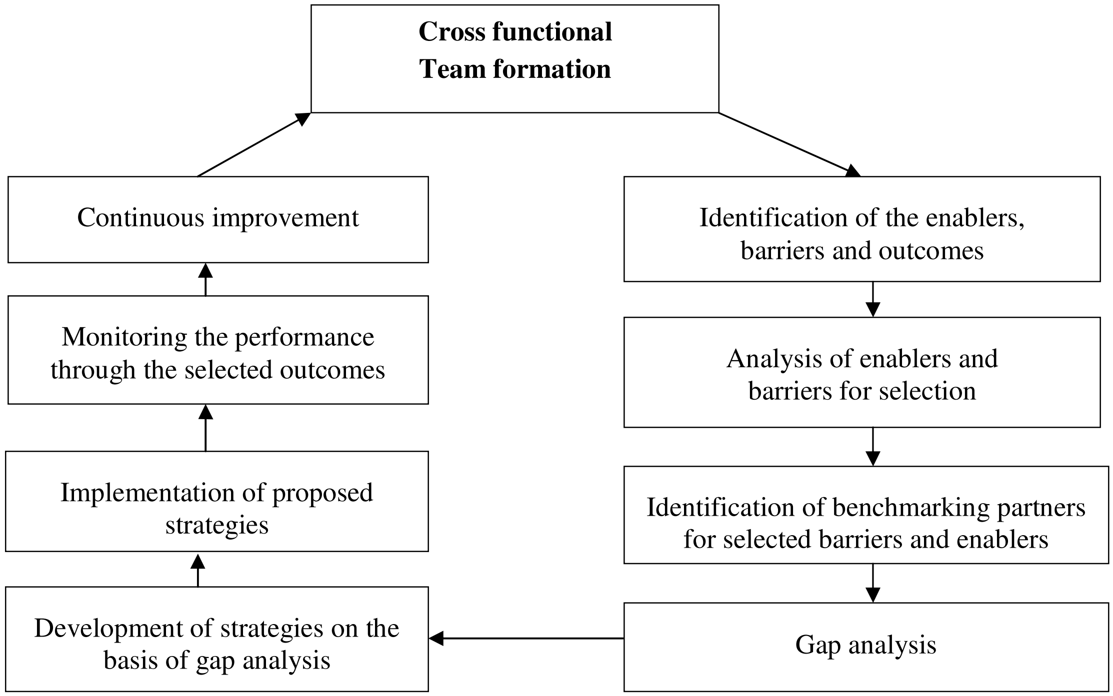

Figure 7.1: Conceptual benchmarking framework of AM for enhancing agility

Table 7.1: Definitions of agility

Author	**Definition**
Gligor *et al*., 2013	Agility is an ability that enabled firms to thrive in an environment of continuous and often unanticipated change.
Jain *et al*., 2008	Agility emphasizes the ability to react effectively to changing markets.
Ismail and Sharifi, 2006	Agility is rapid response to changes in supply and demand.
Lee, 2002	Agility is the ability to quickly react to unexpected shifts in supply and demand.
Gunasekaran and Yusuf, 2002	Agility is an efficient product development system to meet the changing market requirements, maximize the level of customer service, and minimize the cost of goods.
Fowler and Highsmith, 2001	Agility is based on a set of principles that focus on customer value, iterative and incremental delivery, intense collaboration, small integrated teams, self-organization and small and continuous improvements.
Christopher, 2000	Agility means becoming more responsive to the needs of the market is not just about the speed, it also requires a high level of maneuverability.

Author	Definition
Yusuf *et al*.,1999	Agility is a system with flexible technology, qualified and trained human resources, and shared information that responds quickly to continuous and unpredicted changes in customers' needs and desires and in market demand.
Cho *et al*.,1996	Agility focuses on the vibrant changes in markets and the manufacturing firm in question's rapid response.
Kidd, 1995	Agility is a synthesized use of the developed and well-known technologies and methods of manufacturing. That is, it is mutually compatible with lean manufacturing, computer integrated manufacturing, total quality management, material requirement planning, business process reengineering, employee empowerment, and optimized production technology.
Goldman, 1994	Agility is a comprehensive strategic response to fundamental and irreversible changes that are taking place in the dominant system of commercial competition in "first world" economics.
Iacocca Institute, 1991	Agility means a manufacturing system with extraordinary capabilities(i.e. hard and soft technologies, human resources, educated management, and information to meet the rapidly changing needs of the marketplace speed, flexibility, customers, competitors, suppliers, infrastructure, and responsiveness).

Table 7.2: Definitions of agile manufacturing

Author	Definition
Thilak *et al*.,2015	Agile manufacturing is a paradigm that enables an organization to supply products according to the choice and specifications of the customer.
Vinodh and Kuttalingam, 2011	Agile manufacturing is a manufacturing paradigm that enables the companies to respond to the dynamic demands of the customers quickly.
Devor *et al*., 1997	Agile manufacturing is an expression that is used to represent the ability of a producer of goods and services to thrive in the face of continuous change. These changes can occur in markets, in technologies, in business enterprise. It requires one to meet the changing market requirements by suitable alliances based on core competencies, organizing to manage change and uncertainty, and leveraging people and information.
Gupta and Mittal, 1996	Agile manufacturing is a business concept that integrates organizations, people and technology into a meaningful

Author	**Definition**
	unit by deploying advanced information technologies and flexible and nimble organization structures to support highly skilled, knowledgeable and motivated people.
Booth, 1996	Agile manufacturing is a vision of manufacturing that is a natural development from the original concept of "Lean Manufacturing". In lean manufacturing, the emphasis is on cost cutting. The requirement for organizations and facilities to become more flexible and responsive to customers led to the concept of agile manufacturing as a differentiation from the lean organizations.
Cho *et al*., 1996	Agile manufacturing can be defined as the capability of surviving and prospecting in a competitive environment of continuous and unpredictable change by reading quickly and effectively to changing markets, driven by customer-designed products and services.

7.3.1 Research Objectives and Methodology

The different types of strategies, enablers, barriers, outcomes, their importance and impact on the AM performance reported in the literature were studied and analyzed to get more insights related to AM. In this regard, several AM frameworks (see Table 7.3) proposed with an objective to enhance the manufacturing agility level are identified from literatures and studied. However, no generic work has been reported on the application of benchmarking approach in enhancing the manufacturing agility. Therefore, a generic conceptual benchmarking framework for AM is proposed which can serve as a road map for enhancing manufacturing agility. The methodology for developing this proposed benchmarking model is inspired from the pioneering work of Xerox benchmarking model (Camp, 1989); and benchmarking the benchmarking models (Anand and Kodali, 2008). The initial benchmarking model is on the basis of available literatures relevant to AM and benchmarking. Then proposed benchmarking model was discussed and analyzed with experts' (having minimum of ten years of experience) drawn from Indian manufacturing companies with high level of agility or focusing on enhancing agility. After relevant modifications were made in the initial benchmarking model on the basis of experts' opinion, finally a nine-phase and 38-steps generic conceptual benchmarking framework for AM is proposed and is shown in Figure 7.1. The steps of each phase are also discussed, analyzed and documented in Section 7.3.2. Similarly, Routroy and Shankar (2015) proposed a generic benchmarking framework for supply chain risk management.

Table 7.3: Different agile manufacturing frameworks reported in the literature

Author	Major Components	Type of organizational
Gunasekaran, 1998	Co-operation, value based pricing strategies, investments in people and information, and organizational change	Manufacturing firms
Gunasekaran, 1999	Strategies, systems, technologies, and people	Manufacturing firms
Sharifi *et al.*, 2001	Agility drivers the increasing turbulence of the business environment, unpredictable/unprecedented changes in the business environment; strategic abilities widely considered as attributes of agile organizations; agility capabilities responsive, competency, quickness and flexibility; and agility providers organization, people, information systems/technology, innovation	Manufacturing firms
Gunasekaran and Yusuf. 2002	Partnership formation and supplier development; IT in manufacturing; enterprise integration and management with the help of advanced IT/IS; virtual reality tools and techniques in manufacturing; the application of advanced manufacturing concepts and technologies; and global manufacturing/service perspectives	Manufacturing firms
Vazquez-Bustelo *et al.*,2007	Technology; people; knowledge; value chain integration; and concurrent engineering	Spanish manufacturing firms
Dubey and Gunasekaran, 2015	Technologies; empowerment; customer focus; supplier relationship; flexibility and organizational culture	Indian manufacturing firms

7.3.2 Phases and Steps of the Proposed Conceptual Benchmarking Framework of AM

The details regarding proposed conceptual benchmarking framework of AM in terms of phases and steps are mentioned and discussed below.

Phase 1: Cross functional team formation

Step 1 Form a Cross Functional Team (CFT): A CFT should be developed consisting of 4-8 members and members should be selected mostly from procurement, manufacturing, marketing and finance department. The size of the team should be decided depending upon the size of the organizations, nature of products, type of customer etc. Each team member should have sound knowledge and experience about agility and AM. The role and responsibility of each member should be clearly defined. Team leader should be made. The necessary training should be provided to team leader and members depending on their role and responsibilities.

Step 2 Understand the need of benchmarking: The CFT should understand and analyze the need of benchmarking for AM. The objectives and strategic goals of benchmarking should be established and documented considering the manufacturing environment of the company. It should also identify and classify all the AM areas.

Phase 2: Identification of the enablers, barriers and outcomes

Step 3 Establish the set enablers (which have positive impact) on agility: The set of enablers specific to the case company considering business environment should be established taking inputs from CFT and industry experts (preferably from the case company). The generic set of enablers discussed in the Section 2.2.2 may be used as a basis.

Step 4 Establish the set barriers (which have negative impact) on agility: The set of barriers specific to the case company considering business environment should be established taking inputs from CFT and industry experts (preferably from the case company). The generic set of barriers discussed in the Section 2.2.3 may be used as a basis.

Step 5 Establish the set outcomes for measuring agility: The set of outcomes specific to the case company considering its business environment should be established taking inputs from CFT and industry experts (preferably from the case company). The generic set of outcomes discussed in the Section 2.2.4 may be used as a basis.

(The appropriate techniques/approaches (i.e. literature review; scanning of the environment; timed attributed Petri net; information sharing and acquisition; checklists and check sheets; event tree analysis; fault tree analysis, failure mode effect and criticality analysis; failure mode effect analysis; hazard and operability study; expert opinion surveys; and cause and effect diagrams) should be adopted which may be qualitative or quantitative depending upon the environment for finalizing the list enablers/barriers/outcomes.)

Step 6 Fix key performance indicators (KPIs) for each identified enablers, barriers and outcomes: Search should be made in the published information sources like technical and business journals, internal database, external database, experts' opinion etc to fix KPIs for each identified enablers, barriers and outcomes. A set of important KPIs for a few selected enablers, barriers and outcomes are mentioned in Table7.8.

Step 7 Specify measurement unit and data sources for each KPI: The KPIs may be quantitative or qualitative in nature. The intervals of measurement of each identified enabler, barrier and outcome along with its KPIs should be fixed. This will make the analysis easier. The source data collection regarding each KPI should be identified.

Step 8 Determine the data collection method: Once source is identified, the data collection method for each KPI should be decided. The person(s) involved to collect the data for each KPI should be trained (regarding the adopted techniques/approaches/ methods those will be used) and made responsible for its collection. The present performance information along each KPI should be collected and documented.

Phase3: Analysis of selected enablers and barriers

Step 9 Methodology to be adopted for analyzing the enablers: The CFT should decide the methodology(s) to be adopted for analysis of the enablers along various dimensions but not restricted to degree of impact, degree of driving power, degree of dependence power etc along different time line. Various methodologies have been reported in the literature for the analysis of enablers along different dimensions (see Table 7.4).

Step 10 Data collection for analyzing the enablers: The questionnaire should be made to capture the experts' (preferably drawn from the case company) judgment along various dimensions as mentioned in step 9 for the analysis of the selected enablers.

Step 11 Methodology to be adopted for analyzing the barriers: The CFT should decide the methodology(s) to be adopted for analysis of the barriers along various dimensions but not restricted to degree of impact, degree of driving power, degree of dependence power etc along different time line. Various methodologies have been reported in the literature for the analysis of barriers along different dimensions (see Table 7.5).

Step 12 Data collection for analyzing the barrier: The questionnaire should be made to capture the experts' (preferably drawn from the case company) judgment along various dimension as mentioned in step 11 for the analysis of the selected barriers.

Step 13 Selection of right enablers for benchmarking: Using the methodology(s) selected in step 9 and data collected in step 10, the analysis of enablers should be carried out to select the right enablers which should be considered for benchmarking.

Step 14 Selection of right barriers for benchmarking: Using the methodology(s) selected in step 11 and data collected in step 12, the analysis of enablers should be carried out to select the right enablers which should be considered for benchmarking.

Table 7.4: Research reported on agile manufacturing enablers with different objectives

Author	**Objectives of the research**
Kumar, 2015	Proposed a model using genetic algorithm for job shop scheduling to overcome the impact of agile environment such as changing customers' preferences, machine breakdowns, deadlocks, etc. by inserting the slack that can absorb these disruptions without affecting the other scheduled activities.
Kazemi and Seyyedi, 2015	Integrated balanced scorecard with fuzzy AHP and ELECTRE III for prioritize agility dimensions in auto parts manufacturing company.
Holzner *et al.*, 2015	Developed a systematically design approach for flexible and agile manufacturing and assembly systems focusing on small and medium-sized enterprises (SMEs) requirements which were carried out by a questionnaire survey of a sample of several manufacturing SMEs in Italy.
Thilak *et al.*, 2015	Carried out literature review on the origin of AM paradigm and identified its enablers and analyzed the application of AM in pump industry.
Routroy *et al.*, 2015	Calculated the Fuzzy Agile Manufacturing Index FAMI along the timeline considering judgments of multiple experts using combination of fuzzy synthetic extent of weights and average fuzzy performance ratings of AM enablers.
Arvind *et al.*, 2014	Applied graph theory for conceptual modeling of the AM system and to compute the dependencies among the agile enablers.
Saleeshya *et al.*, 2011	Studied the extent to which the AM paradigm is recognized and deployed in Indian manufacturing organizations and also developed a framework to enhance its agility.
Vinodh *et al.*, 2011	Studied and concluded that of computer-aided design (CAD)/computer-aided manufacturing (CAM) technology has the capabilities to infuse agile characteristics in the traditional products.

Author	**Objectives of the research**
Vinodh and Kuttalingam., 2011	Justified computer-aided design and computer-aided engineering as enablers of agile manufacturing.
Bottani, 2010	Investigated empirically taking input Small and medium enterprises of Italy both the profile of agile companies and the enablers practically adopted by companies to achieve agility
Eshlaghy *et al*., 2010	Found out the direct and in-direct effects of the enablers of AM for Iranian industrial organization using case study and path analysis method.
Hasan *et al*., 2009	Determined the relationship among the various enablers for the AM philosophy using Interpretive Structural Modeling India
Vinodh *et al*., 2008	Quantified the agility levels of AM for an electronics switch manufacturing company in India.
Vazquez *et al*., 2007	Analyzed AM enablers empirically taking inputs from manufacturing industries in Spain and found that AM promotes manufacturing competitive strength, leading to better operational, market and financial performance.
Dowlatshahi and Cao., 2006	From several enablers of AM, selected Virtual Enterprise VE and Information Technology IT and studied empirically taking inputs from managers of several AM manufacturing companies in the Midwest region of the United States. They found that both VE and IT had positive influences on business performance for all industries
Yusuf *et al*., 1999	Identified the enablers of AM and discussed the portfolio of competitive advantages that had emerged over time as a result of the changing requirements of manufacturing.
Gunasekaran, 1998	Developed conceptual framework for the development of an AM system to identify the key concepts and enablers.

Table 7.5: Agile manufacturing impediments

Barriers	**Explanation**	**References**
Improper competency management	Manufacturing organization that is not able to leverage or augment its competency will face a difficult task while faced with an uncertain customer demand. It must be open to embrace new technologies and inculcate change management in order to be agile	Gunasekaran, 1998, Gunasekaran, 1999, and Gunasekaran and Yusuf, 2002; Brown and Bessant, 2003; and Guisinger and Ghorashi, 2004;
Improper forecast	Improper assessment of uncertainty, market conditions and the degree of agility required will impact the operations and result in inefficient response to customer	Cochran and Uribe, 2005; and Lin *et al*., 2006
Improper human resource management	Good human resource can contribute towards agility if they are trained to become multi-skilled, motivated and	Sohal, 1999; Brown and Bessant, 2003; and Sumukadas and Sawhney,

Barriers	**Explanation**	**References**
	placed in the right place and numbers	2004
Inefficient information management	Transparence in information sharing in terms of time, accuracy, nature/type, visibility etc is the antecedent for agility in the organization	White *et al.*,2005
Lack of management involvement	Top management support and involvement in maintaining a conductive environment will lead to an agile organization. A management without proper strategy, commitment and plans will fail to leverage the opportunities	Youssef, 1992;Sohal, 1999; Gunasekaran, 1999, Hoek *et al.*, 2001; Hoek *et al.* 2001, Gunasekaran and Yusuf, 2002 and Jin-Hai *et al.*,2003
Lack of manufacturing flexibility	Manufacturing process is the backbone of any agile organization. The manufacturing processes using advanced technologies and equipment will be in a better position to face the agility. Flexible equipment and reconfigurability are the key areas that promote agility	Gunasekaran 1998; Sohal, 1999;Gunasekaran, 1999; Backhouse and Burns, 1999 Yusuf and Adeleye, 2002; Jin-Hai *et al.*,2003; Cochran and Uribe, 2005; and Rao *et al.*, 2006;
Ineffective production planning	Operations planning keeping in view of the changing market conditions and customer preferences are the need for an agile organization. When the planning is bogged down by internal constraints that restrict proper planning and strategies are based on mass production and marketing, then it will have a negative impact on the agility of the organization	Youssef, 1992; Gunasekaran, 1999; Hoek *et al.*, 2001; Gunasekaran and Yusuf, 2002; Brown and Bessant, 2003; Cochran and Uribe, 2005, and Kohand Gunasekaran.,2006
Statutory policies	Need for agility is suppressed if the organization is protected by statutory policies that restrict competition	Sohal, 1999
Improper customer relationship	Better customer relations are necessary to understand their requirements, feedbacks and to address their grievances on time in effective which in turn will enhance agility the organization	Cochran and Uribe, 2005; and Lin *et al.*,2006
Improper supply chain	Collaboration among strategic supply chain partners is the key to be agile. Where the relationship is not nurtured or sustained due to differences in opinions, management or competency, it is difficult to operate as per the plans. This results in an organization losing its agility	Backhouse and Burns, 1999; Gunasekaran, 1999; Sanchez and Nagi, 2001; Yusuf and Adeleye, 2002; Brown and Bessant, 2003; Guisinger and Ghorashi, 2004, Pikkarainen and Passoja, 2005; and Koh *et al.*,2006

Table 7.6: Agile manufacturing outcomes

Outcome	**Explanation**	**References**
Manufacturing performance	It refers to customization, manufacturing capability, manufacturing cost, manufacturing time, change over time make span and process reconfiguration	Ching *et al*., 2006; Ramesh and Devadasan, 2007; Quinn *et al*., 1997; Aruo, 2009 and discussion held with experts.
Financial performance	It relates to profit margin, profit enhancement, economic stability, and economic sustainability	Calvo *et al*., 2008; Aruo, 2009; Thomas *et al*., 2012; Pham *et al*., 2012; Shannon *et al*., 2012 and discussion held with experts.
Marketing performance	It relates to capturing market environment, management of market volatility, improvement in market share, entering new market, response time for customer orders and queries and quick response to market change	Aruo, 2009, Ching *et al*., 2006; Mengoni and Mandorli, 2009; Ching *et al*., 2006; Ramesh and Devadasan 2007; Vinodh *et al*., 2008 and discussion held with experts.
Product development	It relates to product management, product variety, development of new product, product reconfiguration, and design collaboration	O'Grady, 1999; Ching *et al*., 2006, Ramesh and Devadasan 2007; Vinodh *et al*., 2008; Mengoni and Mandorli., 2009; Aruo, 2009 and discussion held with experts.
Customer satisfaction	It relates to customer requirements fulfilled, customer delight, customer retention, and customer base enhancement	Ching *et al*., 2006; and discussion held with experts.
Bottom line performance	It relates to operational performance, operational cost effectiveness and operational effectiveness	Vinodh *et al*., 2008; Hetherington and Ismail, 2007 and discussion held with experts.
Top line performance	It relates sustainable competitive advantage, company performance, level organizational learning, robust operations, fosters innovation, empowered work teams and job satisfaction	Hetherington and Ismail, 2007; Ye-zhuang *et al*., 2006; Shannon *et al*., 2012; Ching *et al*., 2006; Vinodh *et al*., 2008; and discussion held with experts.
Supply chain performance	It relates to upstream relationships, downstream relationships, inventory turns ratio, innovation flow, product introduction time, robust to market changes, information visibility	Gaafar and Masoud, 2005; Vinodh *et al*., 2008, Ribeiro *et al*., 2009; and discussion held with experts.

Table 7.7: Methodologies used for agility assessments of AM

Author(s)	Methodology adopted
Routroy *et al.*, 2015	Used fuzzy synthetic extent of the weights of Agile Manufacturing Enablers AME and the average fuzzy performance ratings of the AMEs to develop a Fuzzy Agile Manufacturing Index FAMI in order to determine the agility level an Indian manufacturing organization along different timeline.
Yauch, 2011	Constructed a quantitative, objective metric for agility performance that assesses agility as a performance outcome, capturing both organizational success and environmental turbulence, and applicable to manufacturing organizations of all types.
Vinodh *et al.*, 2010	Used multi grade fuzzy, fuzzy logic and benchmarking approach for assessment of agility in an Indian manufacturing organization.
Ganguly *et al.*, 2009	Developed a framework and quantify the agility based on agility driver.
Erande and Verma, 2008	Developed comprehensive agility measurement tool to determine responsiveness of an enterprise to external turbulences considering ten agility enablers.
Chandana, 2008	Developed a fuzzy logic, knowledge-based framework for the assessment of manufacturing agility.
Lin *et al.*, 2006	Developed of the absolute agility index, using fuzzy logic to address the ambiguity in agility evaluation.
Tsourveloudis and Valavanis, 2002	Developed a knowledge-based framework for the measurement and assessment of manufacturing agility.

Table 7.8: Key performance indicators for a few selected enablers, barriers and outcomes

	Key performance indicators	Remarks
Manufacturing Performance	Level of customization	Outcome
	Degree of manufacturing capability	
	Manufacturing cost	
	Manufacturing lead time	
	Change over time	
	Process reconfiguration	
Marketing Performance	Capturing market environment	Outcome
	Management of market volatility	
	Improvement in market share	
	Entering new market	
	Response time for customer orders and queries	
	Quick response to market changes	

	Key performance indicators	Remarks
Customer Relationship Management	Complaint management	Enabler
	Customer care	
	Delivery Lead time	
	Delivery reliability	
	Customer involvement	
	Customer satisfaction and delight	
Product and Process Automation	Automated product design analysis	Enabler
	Automated product manufacturing analysis	
	Automated material handling systems	
	Rapid prototyping	
	Quick changeover	
	Automated packaging	
	Computer Aided Process Planning	
	Computer Aided Maintenance Management	
	Computer aided quality control and inspection	
	Automated tracking	
Improper Competency Management	Poor core competency	Barrier
	Difficulty in adoption of advanced technology	
	Difficulty in change management	
Improper Forecast	Impact of uncertainty	Barrier
	Improper Assessment of agility	
	Imperfect market knowledge	

Phase 4: Identification of benchmarking partners for the selected enablers and barriers

Step 15 Identify the benchmarking partners for each selected enabler and barrier: Search should be made in the published information sources like technical and business journals, internal database, external database etc. to identify a set of benchmarking partners for each selected enabler and barrier.

Step 16 Select the benchmarking partners for each selected enabler and barrier: The CFT should select a benchmarking partner for each enabler and barrier on the basis of nature of business environment, accessibility of information etc.

Step 17 Determine the data collection method and collect required information: Collect complete data regarding each KPI relevant to each selected enabler and barrier from benchmarking partners. The right techniques/approaches/methods should be adopted which may be qualitative or quantitative depending upon the environment. The complete information along each KPI from benchmarking partners should be collected and documented.

Phase 5: Gap analysis of selected enablers and barriers

Step 18 Evaluate the current status of selected enablers: For each selected enabler, the key performance indicators should be established (see step 6). The CFT should evaluate the current status of each selected enabler for the case company.

Step 19 Analyze and determine the current status of selected barriers: For each selected barrier, the key performance indicators should be established (see step 6). The CFT should evaluate the current status of each selected barrier for the case company.

Step 20 Determine the gap for each selected enabler and barrier: Compare the current status of each selected enabler as obtained from step 18 and barriers as obtained from step 19 with its corresponding benchmarking partners as obtained from step 15. The competitive gap for each selected enabler and barrier along its KPIs should be established and documented for further analysis.

Step 21 Identify and analyze the gap for each selected enabler and barrier along various dimensions: The CFT should identify the needs for each selected enabler and barrier along various dimensions (i.e. superior practices, methods, procedures, approaches etc.)for the gaps obtained in step 20. The CFT should also analyze the resources needed, organizational changes to be made, internal and external constraints etc. for bridging the gap.

Step 22 Prioritization and selection of gaps to be bridged: Prioritization and selection of gaps to be bridged along various enablers and barriers on the basis of cost to be involved, time, experts opinion, company’s strategy, benefits in terms of dollars etc. Researchers used various methods to prioritize the gaps and for example, Aravind *et al.* (2014) developed hybrid analytic network process (ANP) – fuzzy technique for order performance by similarity to ideal solution (TOPSIS) to prioritize agility gaps in the AM project.

Phase 6: Development of strategies to bridge the gap

Step 23 Development of strategy(s) for bridging gap for each selected enabler: The gap identified in step 22 should be analyzed for the selected enablers. It may not be possible to bridge the entire selected gap at single attempt in many situations.

Therefore, the CFT should define the set point for optimum gap reduction by considering the internal and external constraints for a particular attempt. It should be revisited at different point of time.

Step 24 Development of strategy(s) for bridging gap for each selected barrier: The gap identified in step 22 should be analyzed for the selected barriers. It may not be possible to bridge the entire selected gap at single attempt in many situations. Therefore, the CFT should define the set point for optimum gap reduction by considering the internal and external constraints for a particular attempt. It should be revisited at different point of time.

Step 25 Gain acceptances from top management: The CFT should evaluate the cost of implementation, changes to be made, technology to be adopted etc due tothe adopted strategy(s) as obtained in step 23 and step 24 for each selected enabler and barrier. It should be communicated to the top management and gain the acceptance of it for implementation.

Phase 7: Implementation of strategies to enhance the performance

Step 26 Development of implementation road made of each selected strategies: Each selected strategy in step 23 and step 24 has to be broken into number of functions/practices/processes. Role of concerned departments for each selected strategy should be communicated and documented. Appoint process owners wherever required and detail the implementation process with timeline. It should be documented and made available.

Step 27 Provide training to the concerned employees on these innovative or modified practices: The appropriate consultants or agencies should be contacted to provide training to the concerned employees on these innovative or modified practices so that the adoption of these practices will be smooth and accurate.

Step 28 Fix the roles and responsibility of each process owner: The aim, objectives and outcomes of each process as obtained in step 26 should be established and communicated to the process owner. The role, responsibility and domain of each appointed process owner should be fixed, communicated and documented.

Phase 8: Monitoring the performances using the selected outcomes

Step 29 Development of monitoring plan to access the implementation: The CFT should develop a Team for Monitoring the Implementation (TMI). The TMI should have 5 to 7 (suggestive but it may be increased or decreased depending upon nature and size of the manufacturing organization) members with at least one member should be taken from CFT. The team members should be taken from human resource, operations and finance, procurement department etc.

Step 30 Check and compare the level of implementation according to the defined timeline: The TMI should check the planned happenings and reality. By that process, discrepancies if any will be surfaced and should be analyzed. The implementation timeline as mentioned in step 26 should be revised if required. Reschedule the process, which are still behind schedule and ensure that best practices are fully integrated into process.

Step 31 Monitor the performance of each selected enablers: The TMI should schedule the timeline at which the performance of each selected enabler should be monitored. The TMI also should take inputs from step 6, step 7, step 8 and step 23 for accessing the performances which will help in monitoring.

Step 32 Monitor the impact of barrier: The TMI should schedule the timeline at which the negative impact of each selected barrier should be monitored. The TMI also should take inputs from step 6, step 7, step 8 and step 24 for accessing negative impact of each selected barrier which will help in monitoring.

Step 35 Monitor the performance of AM using selected outcomes and their KPIs: The CFT should identify and select the outcomes and their corresponding KPIs for accessing AM taking inputs from step 5, step 6, step 7 and step 8. The TMI should schedule the timeline at which the performance of outcomes should be monitored. It should be documented and analysis should be carried out for the actual and predicted values.

Phase 9: Continuous improvement

Step 36 Improve continuously by repeatedly monitoring and recalibrating the process: The CFT should recalibrate AM outcomes after benchmarking implementation on a continuous basis and continuously track it till the best practices are fully integrated into the process.

Step 37 Give rewards for recognizing the efforts provided by the benchmarking and implementation team: The CFT in consultation with Human Resource Department (HRD) should structure the reward systems to recognize the efforts of employees/process owners/departments who are directly and indirectly involved in the planning and successful implementation of benchmarking process to enhance agility of AM. The CFT in consultation with HRD and process owners across different processes should nominate rewards to top management at different point of time.

Step 38 Always take suggestions from the employees to improve the AM processes: The CFT should capture, record and propagate the performance improvement happened in general and the agility enhancement happened in specific along many dimensions among to the employees of the organization due to the benchmarking implementation. The CFT should also ask for suggestions related to benchmarking implementation.

The CFT should develop the implementation manual considering all the 38 steps discussed above in consultation with HRD, TMI, process owners and experts (preferably from the case company).

7.4 Conclusions

As manufacturing organizations increase their global presence, there is the need to enhance agility. Therefore, it is essential to check the performance of agility and evaluate the evolution of agility in their respective manufacturing organizations (Routroy *et al.*, 2015). The managers should prioritize the implementation efforts and resources for achieving agility and AM (Hasan *et al.*, 2013). In this paper, detail discussion is made along various aspects such as frameworks, enablers, impediments, outcomes and assessments of AM. Although a few frameworks for AM have been developed and reported in the literatures but benchmarking approach for enhancing agility of AM has seldom been used. Therefore, a generic benchmarking approach for AM of 9 phases with 38 steps has been proposed and discussed. The proposed framework provides a systematic direction for measuring and enhancing agility on a continuous basis. This proposed framework is conceptually developed and not empirically validated. Therefore, the future research lies on its validation in general. The implementation issues of this proposed benchmarking model should be identified and studied in different manufacturing sectors. The right strategies should be designed and developed to address and overcome these issues for its successful implementation.

CHAPTER 8

Conclusions

Agile manufacturing (AM) has evolved as a recognized manufacturing system by the organizations to manage the uncertainties resulting from vacillating market conditions, shortened product life cycle, varying customer demand and obsolete technologies. It has been adopted as a new concept to improve the competitiveness of diverse organizations ranging from manufacturing to service sector. However in reality, many organizations face difficulties during the implementation of AM. These difficulties arise due to improper management of the AM enablers, inability to mitigate the impact of AM impediments, and non-availability of proper methodology for measuring and enhancing AM performance. Several aspects related to the above mentioned issues are systematically addressed so as to ensure positive returns from AM. These issues have been addressed using a systematic approach and analyzed by applying the appropriate tools/techniques/methodology with an objective of agility enhancement in manufacturing environment. Within scope and limitation of the present work, the major deliverables (outcomes) have been summarized along each chapter, starting from Chapter 2 to Chapter 7 as follows.

In the Chapter 2, exhaustive literature review has been carried out for critically analyzing the literature related to various dimensions of AM and to report the findings. The study compiled and analyzed the various reported definitions of AM reflecting goals, principles and scope with a focus on research contributions, research methodologies, regional importance, author profile, type of industry, and different tools, techniques and methodologies used during 1993-2016. The followings findings were drawn from literature review:

- Research on AM is being conducted around the globe. USA has contributed approximately one third of the research on AM followed by UK, India and China.
- Academicians have contributed to a major portion of the research on AM compared to the practitioners. The anomaly could be due to more emphasis given to implementation by practitioners or due to collaboration with academicians who have managed to publish the results.

- Most of the research papers are found to be either descriptive or empirical in nature, with due importance given towards the AM performance measurement and process analysis. Researchers have focused on the real time case studies in different industries to analyze the relevant data.
- The research on AM has shown a boost from the start of 21st century. Manufacturing, automotive and electronics manufacturing industries have been the focus of AM implementations while software, textile-clothing-fabrics, electrical industries and SMEs have implemented to smaller extent. However, the adoption of AM in telecom industry, food industry, casting industry and service industries is not widespread due the fear of high implementation costs and uncertainty of future.
- Multi-Criteria Decision Making (MCDM) tools have been widely used by various researchers to formulate strategies to improve manufacturing agility, to explore relationships among various AM criteria, to develop agility measurement tool etc.

In the Chapter 3, strategies are developed to select and focus the right Agile Manufacturing Enablers (AMEs) on the basis of their interactions for successful implementation of AM and enhancing the organizational agility. ISM - FMICMAC analysis is used to analyze the AMEs on the basis of their driving and dependence power. The methodology is applied to an Indian electrical hardware manufacturing company to streamline its efforts and enhance agility level. The Adaptability (ADP) was concluded as the most influencing AME from the ISM model whereas from FMICMAC analysis, the Devolution of Authority (DOA) along with the other two enablers (i.e. IVT and ADP) were found in driver cluster/quadrant (i.e. high driving and low dependence power). Therefore, these three AMEs were considered as the prerequisite for implementing AM in the case company. The methodology defined is generic in nature and can be successfully applied to any other manufacturing company.

In the Chapter 4, the analysis of Agile Manufacturing Impediments (AMIs) has been carried out using Fuzzy DEMATEL to establish a cause and effect relationship among AMIs. Also the structural relationships among the AMIs were established using ISM – FMICMAC algorithm. The combined Fuzzy DEMATEL with ISM-FMICMAC algorithm has been applied to an Indian automobile manufacturing company. The methodology will help the managers to strategize / prioritize which AMIs to target.

In chapter 5, a methodology for measuring the agility has been proposed by combining the fuzzy AHP with fuzzy synthetic extent of AMEs weight, and the average fuzzy performance ratings of the AMEs to develop Fuzzy Agile Manufacturing Index (FAMI) and its distance with predetermined agility levels was identified. Provisions for measuring the agility at three time intervals, namely, the past, present and the future have been provided. The methodology has been applied to an Indian manufacturing organization and it is found that the agility of the organization has improved from the past and, is expected to continue to improve in the future. This method is easy to use by industry experts as well as academics alike and does not require sophisticated tools for its deployment. In case of a change in AMEs (due to potential environmental changes), the proposed model can effectively calculate the manufacturing agility along the new AMEs with the expert opinion.

In chapter 6, a methodology to quantify, analyze and evaluate the performance of AM along different time periods has been presented using FAHP and PVA algorithms. The methodology has been applied to an Indian auto component manufacturer. The proposed methodology requires pair-wise comparisons of outcomes and their corresponding KPIs, while pair-wise comparisons are not required for alternative analysis. Due to this, only nine pair-wise comparisons matrices need to be made (i.e. one for outcomes and eight for their corresponding KPIs) in order to calculate the normalized weights of the KPIs. The priority weights of the KPIs are calculated considering multiple experts' judgments and their consistency in the judgments using FAHP. These obtained priority weights are used as an input to analyze the performance of the AM using PVA algorithm. The continuous monitoring of Desired Performance Index (DPI) values will help managers to track and monitor the AM performance without actually measuring AM agility which will trigger corrective actions on real time basis. A methodology is also proposed using GTA to assess the implementation performance of AM considering AMEs. A case study of an Indian automobile manufacturing company has been discussed in detail in order to explain the salient features of the proposed approach and get insights to the real life industry scenario. The proposed approach has been found to be quite useful for the managers to measure the implementation performance of an AM program over a period of time and along various situations. The managerial implications of this work are mentioned below:

- It is a generic decision making model to measure the performance of a manufacturing company.
- The obtained outcomes post implementation provides an effective method to evaluate the level of AM implementation and where the company stands with respect to its goal.
- It also tracks the individual AMEs to determine the necessary improvements needed which will form the basis for investment.

In chapter 7, a generic benchmarking approach for AM of 9 phases with 38 steps has been proposed and discussed to enhance agility. The proposed framework provides a systematic direction for measuring and enhancing agility on a continuous basis. Although few works have been reported on agility assessment and enhancement in the literature, they are mostly industry specific. This proposed framework can serve as a road map to enhance agility of AM.

Future scope of research

While conducting case studies in Indian manufacturing industries, the required inputs for the analysis of AM enablers, impediments and outcomes were collected from the employees with experience and knowledge on agility and AM for those industries. Therefore, the results obtained through these case studies have been basically from employees' perspective not from the viewpoint of the top management. Moreover, the number of experts' opinion considered in different discussed case studies may not be optimal and requires further investigation and subsequent analysis. The case studies were based on a single manufacturing organization but several case studies could be carried out for different organizations and for different sectors to draw more generic results. Empirical study on the strength of relationship among AMEs, impediments as well as on the agility performance should be carried out using structural equation modeling and it should be established in various manufacturing environment. The impact of dynamic behavior of AMEs and impediments on agility should also be studied and analyzed using Bayesian networks. The implementation issues of this proposed benchmarking model should be identified and studied in different manufacturing sectors. The right strategies should be designed and developed to address and overcome the issues for its successful implementation.

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List of Publications

International Journal articles (Peer-reviewed) published/accepted

1. Pavan Kumar Potdar, Srikanta Routroy and Astajyoti Behera (2017), “Addressing the Agile Manufacturing Impediments using Interpretive Structural Modeling”, *Materials Today: Proceeding*, Accepted for Publication.
2. Pavan Kumar Potdar, Srikanta Routroy and Astajyoti Behera (2017), “A benchmarking approach for enhancing agility in manufacturing environment”, *International Journal of Productivity and Quality Management*, Accepted for Publication.
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Paper Communicated to International Journal

1. Pavan Kumar Potdar and Srikanta Routroy (2017), “Performance Analysis of Agile manufacturing: A Case Study on Indian Auto Component Manufacturer”, *Measuring Business Excellence* (Minor Revision).
2. Pavan Kumar Potdar and Srikanta Routroy (2017), “Performance Analysis of Agile Manufacturing Enablers: A Graph Theoretic Approach”, *International Journal of Productivity and Quality Management.*

Brief biography of the Candidate

Pavan Kumar Potdar received a Bachelor's of Technology in Mechanical Engineering from Gunnampally Pulla Reddy College of Engineering, Kurnool, Andhra Pradesh and a Master's of Technology in CAD /CAM from J.N.T.U., Hyderabad. Currently, he is pursuing a Ph.D. in Agile Manufacturing (in the Mechanical Engineering Department) at BITS-Pilani, Pilani Campus. He has over 7 years of industrial experience in Production and Fabrication domain, and over 14 years in academics. At present, he is working as Assistant Professor in Mechanical Engineering Department and stationed at Off-Campus Center at Mumbai. His research interests are in Flexible Manufacturing Systems, Operations Management and Manufacturing Management.

Brief biography of the Supervisor

Dr. Srikanta Routroy has received Bachelor of Technology in Mechanical Engineering from College of Engineering and Technology, Bhubaneswar and Master of Technology in Industrial Engineering and Management from IIT, Kharagpur. He has completed his Ph.D. in the area of supply chain management from Birla Institute of Technology and Science (BITS), Pilani in April 2005. At present, he is working as an Associate Professor (Mechanical Engineering Department) in Birla Institute of Technology & Science Pilani, Pilani Campus. He has more than sixteen years of teaching experience. He has reviewed fives books on supply chain management and operations management. He has authored and co-authored more than 90 research papers in refereed National (16) and International Journals (44) and National and International Conferences (30). He has been reviewer of many Journals of International repute like European Journal of Operational Research; Production Planning and Control, Industrial Management & Data Systems; Supply Chain Management: An International Journal, Benchmarking: An International Journal. His name was listed in Marquis "Who's Who in the World", 2008-2012 (25^{th} - 29^{th} Edition). His broad areas of research interest lie in Supplier Development, Supply Chain Management, and Agile Manufacturing. He has completed one UGC major project entitled "Design of Supplier Development Implementation Framework for Indian Manufacturing Industries" and currently working on DST Rajasthan project entitled "Design of Healthcare Supply Chain for Enhancing Availability and Reducing Wastage of Generic Medicines for Rural Areas in Rajasthan". He has guided two Ph.D. and currently four Ph.D. students are working with him. He has guided 15 M.E. Theses and 20 B.E. (dual degree) Theses.