MODELING, ANALYSIS, EVALUATION & SELECTION OF AN AGILE MANUFACTURING SYSTEM

A thesis submitted in the partial fulfillment of the
requirements for the award of degree of

Master of Engineering in

Production & Industrial Engineering

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For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

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DECLARATION

I hereby declare that the thesis entitled "**Modeling, Analysis, Evaluation & Selection of an Agile Manufacturing System**" is an authentic record of my study carried out as a requirement for the award of degree of **Master of Engineering (Production & Industrial Engineering)** at **Thapar University, Patiala** under the guidance of **Dr. V.P. AGRAWAL**, visiting Professor, Department of Mechanical Engineering, Thapar University, Patiala during **July 2012 to July 2013.** The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any other degree.

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This is to certify that the above declaration made by the student concerned is correct to the best of my knowledge and belief.

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ABSTRACT

Agile manufacturing systems are rapidly increasing in number due to ever changing customer demands, shorter product life cycles, higher product variety, economy of production and highly competitive global market. Global competition has forced manufacturing companies to decrease response time (for changes in design, operation, failures etc.) and also reduce lead time to the market. Also, the product life cycle in case of many products has shortened considerably due to continuous advancement in manufacturing technology and variety of products present in the market. So, a manufacturer requires high response, lower lead times along with economical production and best quality. The principles of agile manufacturing fulfill these requirements very well with characteristics such as re-configurability, reusability and scalability.

In this thesis work, an integrated systems model for the structure of the agile manufacturing system in terms of its constituents and interactions between the constituents is developed using graph theoretic approach. The different constituents and the interaction between the constituents are identified and have been represented by graph-based model. The information of the graph is converted into matrix form. The matrix models and the variable permanent function models are developed for carrying out decomposition, characterization, and the total analysis. The terms of permanent multinomial characterize the agile manufacturing system uniquely and are highly useful for computational storage, retrieval, communication, as well as analysis of the structural information of agile manufacturing system. To illustrate the effectiveness of the Graph Theoretical Approach, an illustrative example has also been presented.

A new methodology has been developed for the evaluation, comparison, ranking and optimum selection of an agile manufacturing system from the different alternative designs available in the global market. This proposed methodology is based on Multi Attribute Decision Making (MADM) approach. Pertinent attributes which describe the whole agile manufacturing system are identified in an exhaustive way. A n-digit coding scheme based on all the pertinent attributes for a given agile manufacturing system is suggested, that is useful for the development of a comprehensive database of available agile manufacturing systems, and their subsequent retrieval. The agile manufacturing system selection procedure allows rapid convergence from a very large number of options to a manageable

shortlist of potentially suitable agile manufacturing systems using, elimination search based in few critical selection attributes. Then the selection procedure proceeds to evaluate and rank the shortlisted alternatives by employing the TOPSIS approach. The proposed 3-stage selection methodology is explained with the help of an illustrative example.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Global competition has dramatically increased the need for manufacturing companies to produce high-quality competitively priced products both quickly & efficiently. In the present context, we refer to agile manufacturing as the ability to reconfigure a system quickly & cheaply to assemble a varying part mix. Agility of this type offers the promise of achieving responsive, economical automation of batch production or short life cycle product manufacturing by reusing generic production software & equipment. Therefore, manufacturing companies must possess a new type of production system with characteristics of re-configurability, reusability & scalability i.e. an agile manufacturing system. It is the agile company that can adapt to the changing global markets that will survive and prosper in this new environment of global competition. The ability to be agile requires an organisation with a culture that embraces change, business processes that are designed for change and utilization of the latest enabling technologies to effect the change.

1.2 History of Manufacturing

The manufacturing industry can trace its roots to the late 18th century and the industrial revolution. The beginning was marked by skilled artisans manufacturing by hand. However, in the past two decades or so manufacturing industry has experienced some notable changes, e.g. from mass production through flexible and lean manufacturing towards agile manufacturing philosophy.

1.2.1 Manufacturing systems: changes in methods of manufacturing

- **Mass production:** Mass production is the production of large amounts of standardized products, including and especially on assembly lines. Products produced are discrete in nature and there is no variety. Skilled labour is not a requirement as most of these facilities operate on automatic assembly lines.

- **Flexible manufacturing:** A flexible manufacturing system (FMS) is a manufacturing system in which there is some amount of flexibility that allows the system to react in the case of changes, whether predicted or unpredicted.
- **Computer-integrated manufacturing:** It is the manufacturing approach of using computers to control the entire production process. This integration allows individual processes to exchange information with each other and initiate actions. Through the integration of computers, manufacturing can be faster and less error-prone, although the main advantage is the ability to create automated manufacturing processes. Typically CIM relies on closed-loop control processes, based on real-time input from sensors.
- **Lean manufacturing:** Lean manufacturing is a production practice that considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful, and thus a target for elimination.
- **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 costs and quality.

1.3 Features of various forms of Manufacturing

1.3.1 Conventional Manufacturing

- Machinery used at the time of conventional manufacturing was huge and required lots of personnel for operation as well as maintenance, so skilled labour was a major requirement.
- Downtimes were frequent and repair & maintenance work was depended solely on a single person (foreman). There were no work ethics or training imparted to the workers, so no standard working procedures were followed and safety of the workers was also compromised.
- Although the products produced by the same manufacturer were similar to the naked eye but there was a high product-to-product variation between them.
- There was little or no competition in the market so the products were produced at rates governed by the manufacturer. Even in case of delay, the customer had no choice but to wait.

- Conventional manufacturing was based on the idea that whatever products were produced by the manufacturers was the norm and the customer accepted them as there was little or no choice in the market. In other words, the manufacturer was the dictator of terms.
- There was no manufacturing strategy employed by the manufacturer either for manufacturing or for repair/maintenance work. So different workers approached the problem in their own way.
- There was no provision for customer to send feedback about the product.
- Since manufacturing lacked standard working procedures, quality of the products was not up to the mark.
- The manufacturing floor was not used optimally.

1.3.2 Flexible Manufacturing

- With the introduction of flexible manufacturing system some of the drawbacks of conventional manufacturing were surmounted. The variety of products that could be produced on single machinery increased as now manufacturing took place by computer controlled machines.
- Changeover from one type of product to another required less time so overall manufacturing times were also reduced.
- Since manufacturing times were reduced this meant that the cost per unit product was also reduced.
- As now the computers controlled the machinery and manufacturing was done by part programs, the quality of products improved. Also the product-to-product variation reduced considerably.
- The overall manufacturing system now became more stable and reliable.
- Since products were now produced in batches, the inventories were now reduced to just work in process.
- Products were now manufactured according to a specific manufacturing strategy.

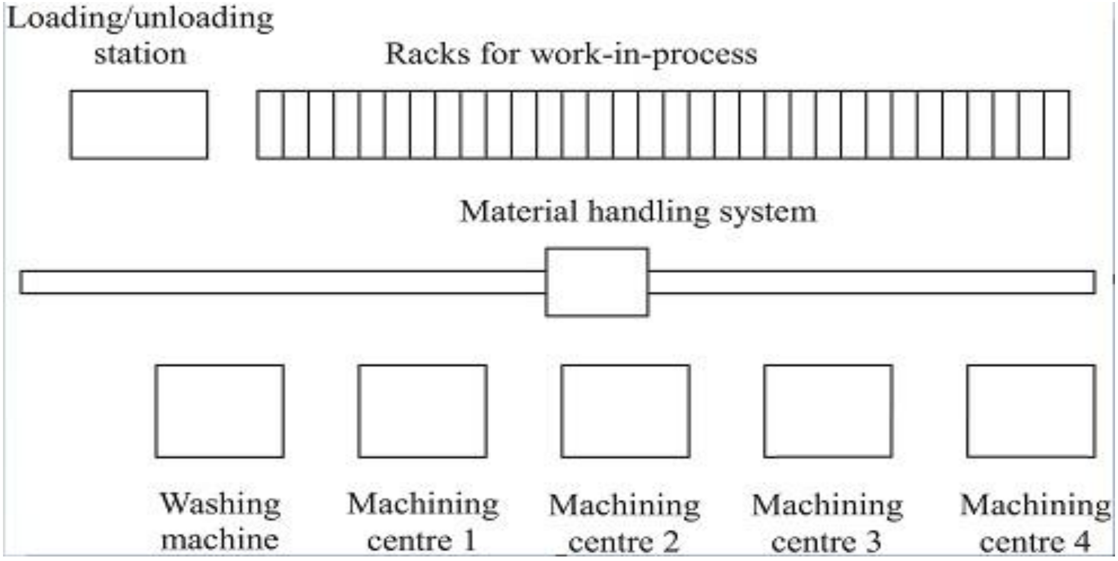

Figure 1.1 Flexible Manufacturing System Configuration

- New product designs could now be processed with ease. It would just require the addition of a new part program for the product.
- Although FMS is very beneficial for a manufacturer its implementation cost is very high. The other factor to be considered before implementing FMS is that it requires a lot of pre-planning before the system can become flexible.

1.3.3 Computer Integrated Manufacturing

- Manufacturing now took place with the integration of computers from procurement of raw material to the dispatch of final product.
- Every process/activity was now integrated with computer. This would mean that the processes were now faster and less error prone.
- The product variety was now even wider than that in FMS and tolerances were reduced further.
- Personnel were required only for supervision of the manufacturing processes. The whole manufacturing as well as repair/maintenance work is automated.

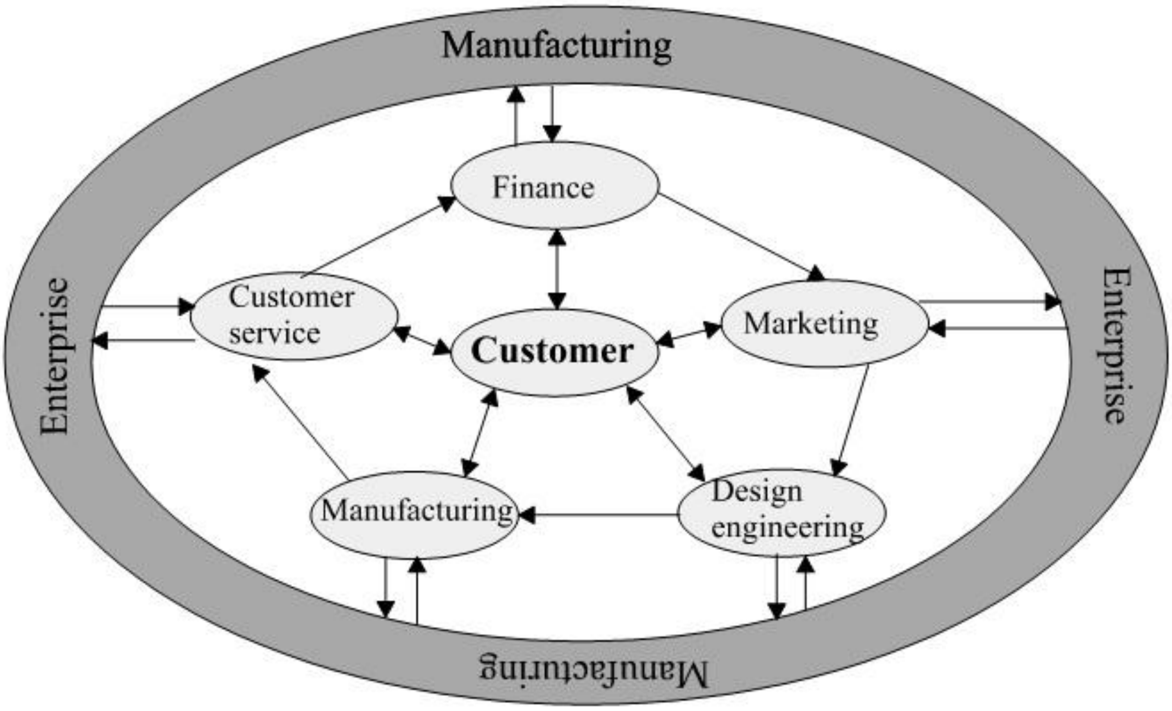

Figure 1.2 Components of Computer Integrated Manufacturing System

- The entire manufacturing processes could be monitored with the help of a single computer integrated with the system. This means that a particular product could be tracked for progress at any time of its manufacturing cycle.
- Since the entire manufacturing system was computer integrated, communication between various departments became easier.
- The cost associated with CIMS is very high.
- CIMS were applicable for products having a long product life cycle.
- The integration of information at various levels of the system is a very tough task.

1.3.4 Lean Manufacturing

- The whole work activities in the plant are categorized as “value added” or “waste” activity.
- Value is defined as any activity that a customer would be willing to pay for.

- The main target is elimination of 8 types of waste (viz. Transportation, Inventory, Motion, Waiting, Over-Processing, Over-Production, Defects & Under utilization of Staff) activities by preserving value with less work (i.e. less human effort).
- The management philosophy of lean manufacturing is derived from Toyota Production System.

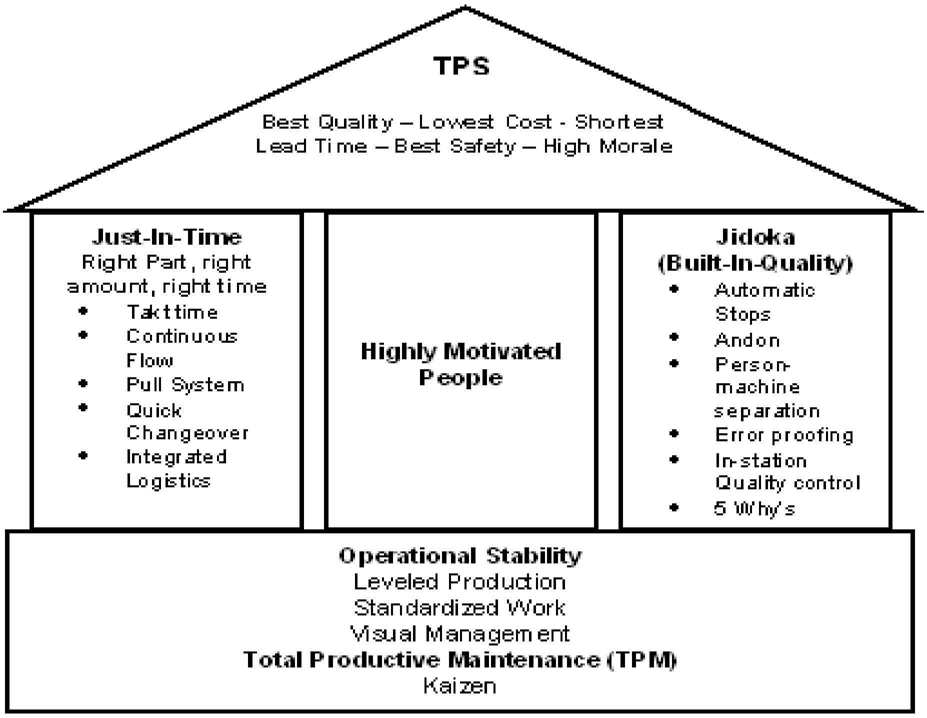

Figure 1.3 The Toyota Production System

- Lean manufacturing philosophy results in better demand management as the customer is the prime focus of the manufacturer.
- Since the customer is the prime focus, another advantage is higher variety of products.
- Space utilization is optimal as a result of elimination of waste.
- Lean manufacturing system follows pull system of manufacturing, hence reducing inventory costs.
- The workers are trained for each process so that a standard procedure is always followed.
- A lean manufacturing environment requires high planning before it can be implemented in a plant.

1.3.5 Agile Manufacturing

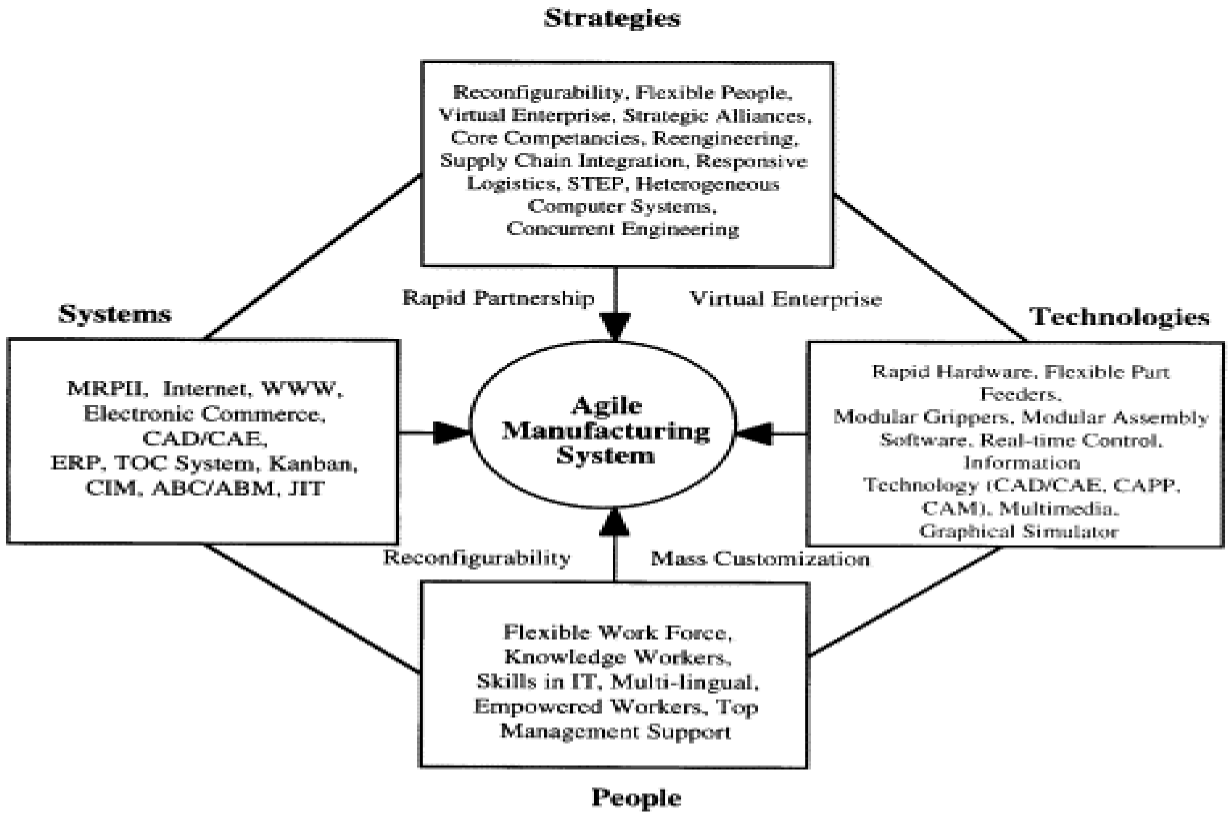

Figure 1.4 Agile Manufacturing System Development

- In today's world the customer has a huge variety of same products to choose from which makes it important for the manufacturer to respond to customer demands quickly and cost effectively.
- An agile manufacturing system enables the manufacturer to respond to customer needs and market changes with ease and low costs.
- A high product variety can be achieved in an Agile Manufacturing System.
- Since the system is capable of responding quickly and easily to fluctuations, the overall efficiency of the system is high.
- The design, planning and production platforms are combined to form an integrated decision platform.
- Principles of reuse, inheritance and encapsulation are applied in order to combine various operations to achieve a high product mix.
- Modular design philosophy is also becoming a part of an AMS nowadays.

It can be said that lean and agile manufacturing are similar in many of the aspects. The main focus in lean manufacturing seems to be on technical and operational issues making it limited to the factory whereas agile manufacturing being broader in scope focuses on the organization and people issues. Lean manufacturing emphasises on minimizing change whereas agile manufacturing embraces change. The capability of an agile manufacturing system to adapt to change depends upon its capabilities to have a flexible production system, to minimize time and changeover cost, to minimize on-hand inventories of finished products and to avoid any other forms of waste, which are the capabilities of a lean manufacturing system. Thus, in order to be agile, the organization must also be lean.

Table 1.1: Comparison of Manufacturing Systems

Conventional Manufacturing	**Flexible Manufacturing**	**Computer Integrated Manufacturing**	**Lean Manufacturing**	**Agile Manufacturing**
Huge machinery	Smaller sized machinery	Smaller sized machinery	Medium to large machinery	Medium sized machinery
High maintenance costs	Lower maintenance cost	Low maintenance sot	Low maintenance cost	Low maintenance cost
Requirement of skilled labour	Lesser skilled labour required	Personnel required only for supervision	Highly skilled labour required	Fairly skilled labour required
No standard working procedures	Standard working procedure	Standard working procedure	Standard working procedure	Standard working procedure
Frequent downtimes	Less amount of downtimes	Very few downtimes	Focus on reducing downtimes	Less downtimes
Compromise with working safety	Safety of workers assured	Safety of workers as well as equipment	Worker friendly environment	Safety of workers assured
Very unreliable system	Increased system reliability	High System reliability	Fair amount of system reliability	Very reliable system
High parts inventory	Reduced parts inventories	Substantial parts inventory	Pull system of production	Low parts inventory
High product-to-product variation	Low part-to-part variation	Lower part-to-part variation	Low part-to part variation	Low part-to-part variation
Higher lead times	Short lead times	Shorter lead times	Short lead times	Shorter lead times
High response time to failures	Moderate response time to failures	Low response time to failures	Moderate response time to failures	Low response time to failures
Little or no product variety	Low variety of products	High product variety	Medium product variety	Fair amount of product variety

Lack of manufacturing strategy	Substantial pre-planning required (i.e. manufacturing strategy)	Manufacturing strategy is always present	Long term strategy for manufacturing	Volatile manufacturing strategy
Reconfiguration not possible	Manufacturing system flexible but not reconfigurable	Reconfiguration not possible at all	Reconfiguration possible to some extent	Totally reconfigurable manufacturing system
High production capability	Medium production capability	High production capability	Medium production capability	Medium production volume capability
Low initial investment cost	High initial investment cost	High initial investment cost	Medium initial investment cost	Medium initial investment cost
Low capability to introduce new models	Medium capability to introduce new models	Low capability to introduce new models	Medium capability to introduce new models	High capability to introduce new models
High cost to introduce new models	Medium cost to introduce new models	Medium cost to introduce new models	Medium cost to introduce new models	Low cost to introduce new models
Low equipment reusability	High equipment reusability	Low equipment reusability	Medium equipment reusability	Medium equipment reusability

1.4 Spider Diagram

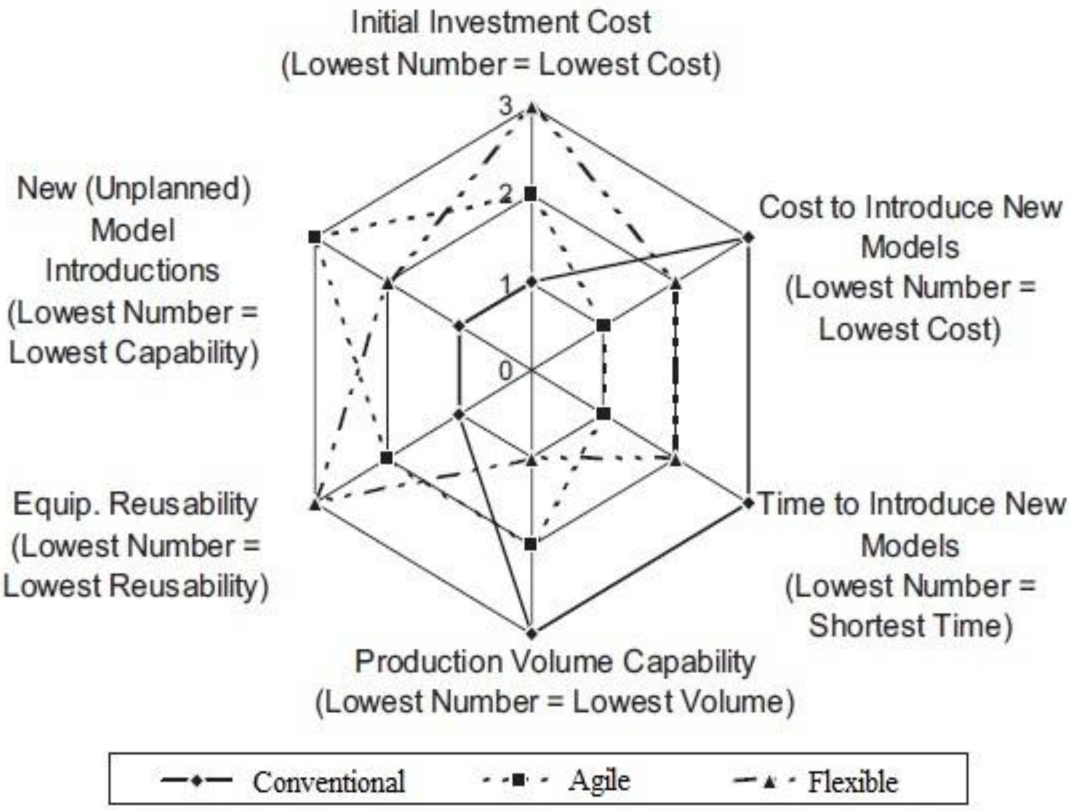

Figure 1.5 Spider Diagram among conventional, Agile & FMS (Debra et al., 2004)

In this method, the attributes of different manufacturing systems have been considered to be forming the spider diagram. So the angle ϴ between the attribute axes can be calculated as $\Theta = 2\Pi/n$, where n number of attributes are under consideration. Here the area enclosed by the polygon formed on the spider diagram is the indication of capabilities of the manufacturing system. Conventional manufacturing systems are perceived to have the lowest investment costs and highest production volume among the three system types. Agile systems have the lowest changeover costs and highest capability to introduce new (unplanned) products. Flexible systems have the highest equipment reusability, but highest investment cost.

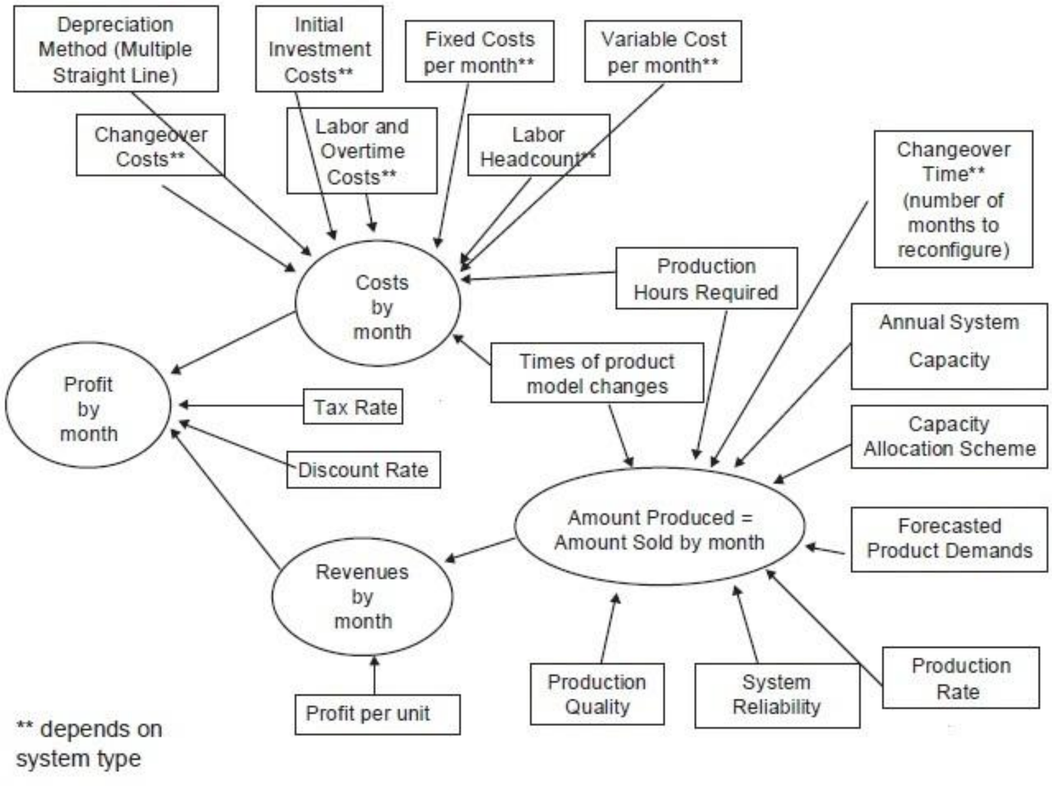

Figure 1.6 Influence diagram illustrating the key data and relationships required to compare different machining systems (Debra et al., 2004)

Using the identified data and relationships as in Fig. 6, the cumulative net present value of profits for systems purchase decisions made under high uncertainty of product volumes, system availability, and timing of mew products introduction can be calculated. Given the demand for each month for each product model, the net profit each month for each system type is calculated as the revenue from product models made and sold during the month less system dependent operating costs, labour costs, tax, depreciation, and changeover costs. Monthly revenues are constrained by labour and production capacity, and may be negative to reflect a lost opportunity, when one system type is down for a changeover, while other system types are able to respond to the changeover more quickly. This lost opportunity cost is specifically included to help differentiate the systems during changeovers. Operating costs include fixed and variable costs for the month the system is in production and only fixed costs for the months a system is in changeover. Labour costs include any overtime costs if necessary to meet production goals. Taxes, assessed on revenues less operating and depreciation costs, may be either positive or negative, depending on whether or not the system makes a profit for the month. Changeover costs are the costs of additional equipment, tooling, and other system modifications, and are assessed during the first month of a system changeover. The cumulative profits over time for each system type is the main result, and is a running total of net profits discounted appropriately.

1.5 Agile Manufacturing: Definition

Agile manufacturing system is defined as a manufacturing enterprise that is "capable of operating in a competitive environment of continuously changing customer demands".

Agile manufacturing system can also be defined as "a production system with characteristics of re-configurability, reusability & scalability." Such a system will allow flexibility not only in producing a variety of parts, but also in changing the system itself.

To remain agile in a competitive environment, the production system must be responsive to frequent changeovers in the production lots and frequent adjustments to the schedule.

Agile manufacturing was produced to adapt to the new characteristics of the present world market, including higher competition, shorter product life cycles, greater product diversity and smaller batch sizes to satisfy a variety of customer profiles.

In years past, manufacturers were the drivers of the supply chain, managing the pace at which products were manufactured and distributed. Today, customers rule the markets, and manufacturers are scrambling to meet customer demands for options, styles and features, quick order fulfilment and fast delivery. In addition, manufacturing systems are also required to be adaptive and agile to cope with not only external turbulence, such as dynamic market changes and technological changes, but also internal uncertainties (e.g. resource shortages or machinery breakdowns). The concept of agile manufacturing has been developed to help manufacturing enterprises achieve positions that can potentially meet global demand The strategy for agile manufacturing must enable the manufacturing systems to be more flexible, responsive and re-configurable to highly variable demand patterns and product mixes, shorter design and manufacturing lead times, better utilization of resources, etc.

1.6 Objectives and proposed methodology

The objective of the present study is the selection of an optimum agile manufacturing system so that time and cost involved are both minimized. This can be achieved by determining the appropriate agile manufacturing system configuration. The configuration has to match the characteristics of the product to be manufactured, market conditions, available resources etc.

Also, the characteristics have to up to date with the business competition. The first step in order to achieve the best configuration is to identify the alternative solutions. The alternatives can then be evaluated and improved and consequently the best configuration can be chosen.

Also, several models have been developed in order to study the integrated system as well as the interaction between the different parts of the agile manufacturing system. Some tools focus on the design and operation of the agile manufacturing system and others are converged towards a particular subsystem oriented design. So, it is realized that approaching the system as a whole is absolutely indispensable in order to acquire a better picture of the operation of every system component and the interaction between them.

Based on the above requirements, the objectives of this thesis are:

- To develop an integrated systems model for the structural analysis of agile manufacturing system, which integrates the different constituents of the agile manufacturing system and describe the whole system while taking into account the effect of interaction between these constituents for the better understanding of the structure of the agile manufacturing system.

In order to achieve this objective, the system approach named **Graph Theoretic approach** is implemented, which includes:

I. Identification of different components or subsystems constituting the agile manufacturing system.
II. Identification of interactions between these different components.
III. Representation of components and their interactions by graph.
IV. Development of matrix models and the variable permanent function models to carry out decomposition, characterization, and the total analysis.

- To develop a methodology by which design, evaluation and selection of agile manufacturing system can be made comprehensive and easy, considering various factors affecting the selection.

In order to achieve the above objective, the system approach named **Technique for order preference by similarity to ideal solution (TOPSIS) a Multi-Attribute Decision Making approach (MADM) approach** is proposed, which includes:

I. Identification of attributes of agile manufacturing system under various subsystems affecting the overall system.

II. Development of n-digit coding scheme to collect the information about the each attribute.

III. Development of TOPSIS procedure for attribute based evaluation, comparison, design improvement and ranking of feasible alternatives.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Agile manufacturing is still a developing field of manufacturing with very wide and diverse applications. A lot of work has been done on various aspects of agile manufacturing in the past. This chapter covers the literature on development of various models, agents, technologies and approaches for improving reliability, efficiency, quality and other aspects of agile manufacturing systems. Also the review of system approaches used in the proposed work has been included.

2.2 Categorization of Literature

The literature has been categorized under the two following categories:

1. General Literature review about agile manufacturing systems.
2. System approach (MADM–TOPSIS and Graph Theoretic approach).

2.2.1 General Agile Manufacturing Systems

Wang et al., (2002) have presented various system models such as domain-based hierarchical structure (DBHS), cascading agent structure (CAS), proximity relation structure (PRS) and bus-based network structure (BNS) for agent based modeling and mapping of a manufacturing systems. The authors have constructed a mechanism for the agents that include functionality, status, capacity and the physical relationships and interactions between agents. Reconstruction and reconfiguration based on multi-agent ontology is a novel approach, especially in different infrastructures of agents. With the help of these models dynamical rebuilding of a manufacturing system is possible via simulation.

Yang & Li (2002) have studied MC enterprise's organization management agility evaluation; MC products design agility evaluation and MC manufacture agility evaluation to develop MC product manufacturing agility evaluation index system. They have improved the research achievement of agility assessment of an MC manufacture system achieved by Amos and Dove, etc., and have simultaneously suggested the establishment of an evaluation index system of MC product manufacturing based on the characteristics of MC product manufacturing and the requirements of agility manufacturing. This evaluation index system of MC product agility manufacturing is formed by three aspects, including enterprise organization management, products design & processing and manufacturing. Then the multi-grade fuzzy assessment method is used to evaluate the MC products manufacture agility of Xi Dian Casting Limited Company. The research in this paper has an important theoretical role in guiding MC enterprises in realizing their agile manufacturing abilities.

HE & Grigoryan (2002) have developed double sampling s-charts for quick detection of small shifts in process standard deviation for agile manufacturing systems. The construction of the double sampling s-charts is based on the same concepts in constructing the double sampling $\bar{x}$ - charts and is formulated as an optimization problem and solved with a genetic algorithm. Then the efficiency of double sampling s-control charts is compared with that of the traditional s-control charts. the results show that double sampling s-control charts can be a more economically preferable alternative in detecting small shifts that traditional s-control charts.

Uribe et al., (2003) presented a practical modeling technique for minimizing the required investment in capacity planning for discrete manufacturing sites under an uncertain demand stream. The method consists of a two-stage stochastic integer program. The model is scalable, allowing for multiple products, multiple operations, multiple flow paths including re-entrant flow and multiple tool types. The researchers are pursuing additional research opportunities in this modeling such as including setup times, batching policies, dispatching policies and analysis of demand variability at different levels.

Lim & Zhang (2003) have developed a multi-agent framework in which process planning and production scheduling are integrated, as a preliminary step towards agile manufacturing. This framework would also allow utilisation of manufacturing resources to be dynamically optimised as well as provide a platform on which alternative configurations of manufacturing could be assessed. This framework enables alternative machine grouping and scheduling options to be evaluated dynamically in response to market changes.

Yao & Carlson (2003) studied a furniture production system that had implemented the concepts inherent in MRP, TQM and JIT while recognizing the need for agility in a somewhat complex and demanding environment. They emphasised on the fact that the key to balanced and synchronised production is the lot size. The company can behave as agile through its flexibility in responding to market and schedule changes and as lean by focussing on minimizing various wastes.

Wang et al., (2003) proposed a multi-agent and distributed ruler based approach to production scheduling in agile manufacturing systems. With the distribution of agents and rulers, the complicated agile scheduling problem can be divided into several problems, such as decision-making problems for each individual agent, from the agent's perspective and coordinating problems between agents for the global goals of the whole system. The simulation results have demonstrated that the approach is capable of generating feasible schedulers in agile manufacturing environments.

Elkins et al., (2004) have discussed agile manufacturing systems from an automotive industry perspective. A descriptive influence diagram, spreadsheet model and a tree diagram are studied to gain understanding about the value of system agility. From the study presented in this paper agile systems seem to meet the promise of new product model introductions and dynamic capacity allocation to meet unpredictable demand. The two decision models developed are simple; capture the important features of economic decisions about manufacturing systems and facilitate discussion with automotive industry engineers about agile an FMSs. However, there is a significant opportunity to extend research to more fully address the business case for agility.

Ip et al., (2004) presented an investigation on the partner selection problems with engineering projects. The partner selection problem is described by a 0-1 integer programming with non analytical objective function and then proven as an earliness and tardiness production planning problem. A solution space is developed by introducing the concept of inefficient and ideal candidates which reduced the complexity of the problem. Then a branch and bound algorithm embedded project scheduling is developed to obtain the solution. Although the computational results were found to be satisfactory, the criteria used to select partners in a real life perspective usually include quality, serve, credit and more factors besides cost and completion time. The quantification of these attributes is a bit difficult and subjective.

Lim & Zhang (2004) presented a paper aiming to develop a system to integrate dynamic process planning and dynamic production scheduling for the purpose of increasing the responsiveness of agile manufacturing systems in accommodating dynamic market changes.

The concept of Multi-Agent Systems (MAS) has been adopted in the study. This system does not only integrate dynamic process planning and scheduling, but also optimises machine utilisation and provides a platform to assess the reconfiguration of manufacturing systems. The system implementation has been carried out as results obtained show that via the co-ordination between agents, an optimum/near optimum integrated plan and schedule can be produced, which carries the best compromise of the four important criteria.

Lee et al., (2004) introduced a dynamic data interchange scheme which attempts to exchange data automatically as well as enables the filtering of valuable data between traditional relational database model and case based reasoning knowledge repository. The significance of this paper is concerned within a hybrid database system, embracing the empirical data to help agile manufacturing enterprises make critical decisions. A Dynamic Data Interchange Scheme (DDIS) is introduced for supporting data integrity between Relational Database Module (RDM) and Knowledge Storage Module (KSM), thereby accelerating the product development process in which every functional entity of a company is involved. Further research on the reliability of data exchange between KSM and RDM is required to enhance the effectiveness of the whole system.

Guisinger & Ghorashi (2004) have presented a study to examine the trends in the specialty chemical industry that have led to the rising number of agile practices and virtual organisations. The current state of the industry is also presented. The five most prevalent agile practices in the chemical industry are: custom chemical manufacturing; improving supplier relationships; formation of strategic partnerships; adaptation of advanced technology/research and emergence of virtual firms. A comparison of this company with the case studies have revealed how a small-intermediate size manufacturer can properly implement many agile manufacturing practices and position itself for growth and competitiveness in its category and class.

Wu & Su (2005) have modelled the partner selection problem by an integer programming formulation to minimize the manufacturing cost. Completion time has been taken as a constraint. The formulation developed is then transformed into a graph-theoretical formulation and a 2-phase algorithm is developed to solve the problem. In the first phase, a polynomial bounded algorithm is proposed to find the earliest completion time to obtain a feasible solution. In the second phase, the solution is improved by exchanging the candidate partners by keeping the solution in the feasible region. Although the optimal solution is not found for the problem by the improvement algorithm, the objective is reduced iteration by iteration. The algorithm is efficient and can be applied to practical problems.

Cao & Dowlatshahi (2005) have explored the link between information technology (IT) and virtual enterprise (VE) and the impact of this link on business performance within the context of agile manufacturing research. The paper provides a conceptual framework to systematically explore the relationship between agile manufacturing and business performance and also provides empirical evidence and detailed statistical analysis for the relationships between various constructs involved. The results indicate that both VE and IT have a positive impact on business performance. It is also shown that the impact of alignment between VE and IT on business performance is more significant than that of VE and IT on business performance individually.

Devadasan et al., (2005) developed a modified orthogonal array-based model for enabling the researchers and practitioners to exploit the technique, “design of experiments” in an agile manufacturing environment. The characteristics of Taguchi’s offline models and agile manufacturing are used to develop the model which is subjected to study in an Indian pump manufacturing company. The model presented is helpful in achieving quality standards in agile manufacturing environment.

Vonderembse et al., (2006) described a typology for designing supply chains that work in harmony to design, produce, and deliver products with different characteristics and customer expectations. This research discusses supply chain types that are necessary for success across three types of products: standard, innovative, and hybrid. It develops a framework for categorizing the supply chain types according to product characteristics and stage of the product life cycle. The key success factor for a product change as the product moves through its life cycle, and this may require different supply chain characteristics and capabilities. This research provides insights for discrete part manufacturing firms that design, implement, and participate in supply chains. It defines the characteristics for standard, innovative, and hybrid products, and it provides a framework for understanding lean and agile supply chains. LSCs employ continuous improvement efforts and focus on the elimination of non-value added steps across the supply chain. ASCs respond to rapidly changing, continually fragmenting global markets by being dynamic, context-specific, growth-oriented, and customer focused.

HSCs combine the capabilities of lean and agile supply chains to create a supply network that meets the needs of complex products.

Palacios et al., (2006) have presented a paper based on results obtained and lessons learned over 2.5 years of recent multidisciplinary research in development of agile and flexible scheduling tool for turbulent environments in the extended enterprise at Robotiker and the University of Deusto (Spain). The main result of IS-OPTIMUS is an IT-based dynamic scheduling tool for multi-site manufacturing environments, which consistently generates, even under changing production conditions, fast, flexible and optimised schedules. It takes into account the importance of product mix and short lead times combined with delivering optimum cutting patterns and product arrangements for the processing of 2D board components. IS-OPTIMUS is a general tool, applicable in a wide range of industrial sectors, and is mainly tailored to SMEs. Such technologies have been extensively tested at three industrial sites, and have provided significant improvements in terms of better machinery utilization, lead times reduction, and less material waste.

Tanimizu et al., (2006) proposed a new reactive scheduling method based on the Genetic Algorithm (GA), which generates improved production schedules reactively against the disturbances. The proposed method continuously creates new feasible production schedules, until a new production schedule satisfies the given constraint or all the manufacturing operations have started. This paper deals with a new evolutional method to improve the performance of the GA-based reactive scheduling process for adding new jobs. Several computational experiments were carried out for the delays of manufacturing operations and the addition of new jobs by using the developed prototype system for reactive scheduling, in order to verify the effectiveness of the proposed method.

Yauch (2007) has attempted to analyse the team attributes necessary to facilitate agile manufacturing. Using balance theory as a framework, the potential positive and negative impacts related to those team attributes are evaluated that could alter the balance of work system elements and resulting "stress load" experienced by workers. The teams are characterized as multifunctional, dynamic, co-operative and virtual and four team attrinutes necessary to facilitate agile manufacturing have been analyzed.

Bustelo et al., (2007) have analyzed agile manufacturing as a new production model resulting from a break with mass production system and its implementation in Spain. A conceptual model was presented for analyzing agile manufacturing which was tested in a sample of the largest manufacturers in Spain. The multi-dimensional nature of agile manufacturing was confirmed by drawing up a measurement scale based on integration of both structural and infrastructural manufacturing practices. This study adopts a systematic approach to the analysis of agile manufacturing, considering various agility practices or enablers in an integrated way and relating them not only to elements in the environment but also to outcomes.

Gaafar et al., (2008) have presented a methodology in which genetic algorithms were applied to solve the scheduling problem of a manufacturing system consisting of machining and assembly stages, with the objective of minimizing the make span. Genetic algorithms were applied in two ways: general and modified. The general application followed the common gas approach while the modified application was inspired by the particle swarm optimization approach. Various modification were tried before settling on the reported approach where chromosomes in the initial GA population were treated as particles in a swarm and future generations were created by crossing each particle with its local best solution and the global best solution. The results also show that the most significant factor affecting the performance of all available heuristics is C (the ratio of average machining time per part to average subassembly time per subassembly in a digraph). The higher this ratio, the better the chance that an optimum schedule is found. Experimentation results also show that MGA outperformed GGA in response values and in robustness.

Fung et al., (2008) have presented a multi-stage cell formation methodology which can help in selection of appropriate resources and formation of virtual cells. First, appropriate resources for completing production tasks are selected by a LP model considering the available capacity and the costs. In order to form VC in a logical mode, parts having alternative product process routings as multi-functional machines are analyzed by a resource element approach. Furthermore, some routing-based heuristic rules are introduced to optimize the candidate VCs in the form of resource elements. Finally a case study is used to illustrate the detailed formation methodology. The proposed algorithm can be applied to agile manufacturing system to facilitate the production of a diverse variety of products subject to disturbances and changes during manufacturing. Certainly, other rules for optimizing the candidate cells can also be introduced to the algorithm to improve the results.

Blanc et al., (2008) have presented a manufacturing execution system (MES) using the HMS concepts and have illustrated this approach on a real industrial application. Mechanisms are proposed to synchronise the execution of manufacturing tasks. These mechanisms guarantee the availability of components and enable to impose time constraints on task scheduling. This MES implements a product-centred approach, as shown by the active and opportunistic behaviour of order holons. The use of holonic structure allows building a reactive and re-configurable control, while considering global aspects of the manufacturing system.

Wang (2009) has presented a 2-tuple fuzzy linguistic evaluation model for selecting appropriate agile manufacturing system in relation to mass customization production. A mass customization manufacturing agility evaluation approach based on concepts of TOPSIS is proposed through analyzing rhe agility of organisation management, product design, processing manufacture, partnership formation capability and integration of information system. The 2-tuple fuzzy linguistic computing manner to transform the heterogeneous information assessed by multiple experts into an identical decision domain is inherent in the proposed method. It is expected to aggregate experts' heterogeneous information, and offer sufficient and conclusive information for evaluating the agile manufacturing alternatives. And then a suitable agile system for implementing MC can be established.

Bal & Hashemipour, (2009) have presented a methodology based on VR for implementation of the holonic control for real manufacturing practice. The virtual holonic factory concept has been introduced, which integrates VR-based modeling into an agent platform in order to realize the holonic manufacturing control within a discrete event simulation environment. A case study has been performed in a medium size die-casting factory in order to demonstrate the effectiveness of the proposed method in the SMEs. The effect of holonic control has been investigated through several quantitative and qualitative performance measures by the use of the virtual holonic factory. Virtual holonic factory facilitates exploration of the discrete event simulation results and communicate implications associated with design changes to others not as familiar with discrete event programming. Immersion in the virtual factory facilitated the exploration of design changes and their effect on the simulation. There were many variables in this situation which could be changed for each round of iteration. The virtual holonic factory experience guided the users into making informed decisions on where to look for the development of holonic manufacturing control systems for performance improvement. There are some aspects of the visualization of a simulation that the virtual holonic factory has not fully explored and are currently being developed.

Bartholdi III et al., (2010) have presented a study of self organising logistics systems. Further they added that when a logistics system is ‘‘self-organizing’’ it can function without significant intervention by managers, engineers, or software control. The social insects, such as ants or bees, provide models of self organizing logistics systems that may be profitably emulated. Some of these ideas for the problem of balancing assembly lines have been illustrated.

Yimer & Demirli (2010) have formulated a 2-phase mixed integer linear programming (MILP) model for material procurement, components fabrication, product assembly and distribution scheduling of a BTO supply chain system. In the proposed approach, the entire problem is first decomposed into two subsystems and evaluated sequentially. The first phase deals with assembling and distribution scheduling of customizable products, while the second phase addresses fabrication and procurement planning of components and raw-materials. The objective of both models is to minimize the aggregate costs associated with each subsystem, while meeting customer service requirements. The search space for the first phase problem involves a complex landscape with too many candidate solutions. A genetic algorithm based solution procedure is proposed to solve the sub-problem efficiently.

Zandi & Tavana (2011) have presented a novel structured approach to evaluate and select the best agile e-CRM framework in a rapidly changing manufacturing environment. The e-CRM frameworks are evaluated with respect to their customer and financial oriented features to achieve manufacturing agility. Initially, the e-CRM frameworks are prioritized according to their financial oriented characteristics using a fuzzy group real options analysis (ROA) model. Next, the e-CRM frameworks are ranked according to their customer oriented characteristics using a hybrid fuzzy group permutation and a four-phase fuzzy quality function deployment (QFD) model with respect to three main perspectives of agile manufacturing (i.e., strategic, operational and functional agilities). Finally, the best agile e-CRM framework is selected using a technique for order preference by similarity to the ideal solution (TOPSIS) model.

Inman et al., (2011) have developed a structural model incorporating agile manufacturing as the focal construct is theorized and tested. The model includes the primary components of JIT

(JIT-purchasing and JIT-production) as antecedents and operational performance and firm performance as consequences to agile manufacturing. Using data collected from production and operations managers working for large U.S. manufacturers, the model is assessed following a structural equation modeling methodology. The results indicate that JIT-purchasing has a direct positive relationship with agile manufacturing while the positive relationship between JIT production and agile manufacturing is mediated by JIT-purchasing. The results also indicate that agile manufacturing 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. While the objectives of the study were successfully accomplished, limitations of the study should be noted. The response rate raised concerns of potential non-response bias. There is concern that the measurement scales conceptualizing the JIT-related constructs were borrowed from different research streams and that the formats and structuring of the scales is inconsistent. This study links JIT practices to manufacturing agility and agility to performance. Additional research aimed at verifying these results is necessary.

Zhang, (2011) has presented a case-based investigation of the practical details of the three basic types of agility strategies. Typical cases from the basic strategy types were chosen and studied to establish why companies choose each type of the strategies, what distinctive agility drivers they are faced with and why, and whether and what typical action programs are used to implement the strategies. A cross-case analysis found that the choice of agility strategies is related to the nature of markets and competition, the characteristics of products (life cycles and degrees of maturity), and market positions of individual companies.

Fu et al., (2012) have presented a novel methodology for the design of such a flexible super WRND has been developed. It simultaneously considers the integration of multiple WRNDs and network control switch based on different manufacturing purposes. Based on the methodology, the minimum number of regular and three-way valves are optimally placed to minimize the total valve-switching times (TVST) to swap one pair of WRNDs at a time. It deals with the request of multi-purpose production processes, which needs the process itself having the maximum flexibility to handle various production-recipe based tasks. The developed systematic methodology is general and thus applicable for many potential network integration problems. Case studies have demonstrated the efficacy of the development and its significance in the context of agile manufacturing.

Hasan et al., (2012) have introduced a strategic decision model to help manufacturing managers strategically implement agility in their organization by selecting the most appropriate production layout by making use of the Analytical Network Process (ANP) which captures interdependencies among different criteria, sub-criteria and dimensions, an evident characteristic of production flow layouts in complex agile manufacturing environments. The model developed in this study focuses on the selection of an appropriate production flow layout in an agile manufacturing environment. The approach in this study has been bottom to top in the sense that this model was developed to check the decision of the case company to implement the Hybrid Cellular Layout. The major limitation of this study is the ability of the model to be generalized for other situations.

Costantino et al., (2012) have presented a paper that addressed the configuration problem of manufacturing supply chains (MSC) with reference to the supply planning issue. They presented a technique (based on the assumption that the manufacturing system is composed of different stages) for the strategic management of the chain addressing supply planning and allowing the improvement of the MSC agility in terms of ability in reconfiguration to meet performance. The resulting methodology is quite flexible in building the optimization constraints, improving agility in terms of performance and re-configurability in the MSC design.

2.2.2 System Approach

2.2.2.1 Graph Theoretic Approach

R.K. Garg et al. (2006) developed a deterministic quantitative model based on graph theoretical methodology to compare various technical and economical features of wind, hydro and thermal power plants and also used to evaluate and rank the power plants in ascending or descending order in accordance with the value of their suitability index. It is concluded by the authors that the methodology present in this paper allows a decision maker to perform, not just a general analysis, but also other various focused analysis regarding his personal preferences.

R.T. D. Prabhakaran et al. (2006) developed an integrated systems model for the structure of the composite product system in terms of its constituents and interactions between the constituents and the molding processes, curing kinetics etc. using graph theory and matrix algebra. This proposed systems methodology for developing a composite product considered all attributes responsible for design, production, and process parameters. The composite product is first modeled with the help of graph theory, then by variable adjacency matrix and then by a multinomial known as permanent function. The permanent function has provided an opportunity to carry out structural analysis of the composite product in terms of strength, weakness, improvement, and optimization by correlating the properties of a composite with its structure.

Varinder Singh and V.P. Agrawal (2008) have presented a methodology that builds a flexible and comprehensive model of manufacturing system, which has the capability to consider the interdependencies between its various subsystems. After the identification of elements constituting a manufacturing system and the interactions between them, it has been represented by graph-based model. Also the matrix models and the variable permanent function models have been developed to carry out decomposition, characterization and the total analysis. Structural patterns and combination sets of subsystems interacting in various ways have been recognized as capabilities of manufacturing system in different performance dimensions. The permanent function of the manufacturing system matrix has been proposed as a systematic technique for structural analysis of manufacturing system.

C.P. Kiran et al. (2011) presented a novel methodology which combines all the design aspects together to generate a useful form of solution for the mechatronic industry. This methodology concurrently considered all the x-abilities/design aspects along with interactions without missing any useful information and hence leaded to a high quality product. The methodology presented in this paper consists of graph theory, matrix algebra, and permanent multinomial. Eight x-abilities namely, miniaturization, intellegence, integration, environment, quality, reliability, manufacturing, and assembly for concurrent design of a mechatronic system and the design parameters under each x-ability are identified. Also a colour graph is proposed for visual analysis.

2.2.2.2 Multi – Attribute Decision Making (MADM)–TOPSIS

Ashish Bhateja et al. (1996) presented a methodology for total design and evaluation of optimum spring based on multiple attribute decision making (MADM) approach, taking into account various design attributes at the conceptual stage of the design itself. Springs were first coded using a comprehensive attribute based three tier coded structure presented in the form of an algorithm. ‗Elimination search' algorithm is presented for the rapid convergence of very large number to a manageable short-list of potentially suitable springs based on a few pertinent attributes. The short-listed alternatives are ranked on the basis of suggested merit index, by using a MADM method termed TOPSIS. At the last, it is concluded that the method is efficient and may easily be developed into an expert system for total design of springs, providing to be of immense use to the user and manufacturer alike.

P.P. Bhangale et al. (2004) have solved the robot selection problem which arises due increasing complexity, available features, and facilities offered by different robotic products. The objective of their research is to generate and maintain reliable and exhaustive database of robot manipulators based on their different pertinent attributes. That database can be used to standardize the robot selection procedure when the manufacturing firm has decided to use the robot for a particular operation. The methodology presented in this paper can help the robot user to save time by providing him a tool for selecting the robot system most suited for his operational needs. This paper presented a robot selection procedure based on the Multiple Attribute Decision Making (MADM) approach. Here by identifying 83 attributes of the robots, the attempt has been made to codify most of the robot characteristics, which will define the robot precisely and accurately. The coding scheme is illustrated with example of selecting a robot for some pick-n-place operation. It has presented the result of the information processing in terms of a merit value, which is used to rank the robots in the order of their suitability for the given application.

R. T. Durai Prabhakaran et al. (2006) described a methodology for evaluation, coding, ranking, and optimum selection of subsystems for composite product used directly by its manufacturers. The 77-attribute electronic coding scheme and the evaluation techniques are presented in this paper and are useful to the designer during all the phases of design process, and manufacturer for the selection of optimum subsystems, which meet global market requirements. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a Multiple-Attribute Decision Making (MADM) approach is used for selection of subsystems for a composite product development in order of preference for given application. Two graphical methods of MADM approach for evaluation and comparison are also introduced by the authors. It is recommended in this paper that manufacturer of composite product should develop attribute-based specification in the form of proposed coding scheme. This will directly help industry in carrying out SWOT (Strength– Weakness–Opportunities–Threats) analysis from the point of view of its manufacturing and business strategies.

R.K. Garg et al. (2007) presented a computational methodology for a computer-based solution to the problem of evaluation and selection of an optimum power plant. This methodology is named as multiple attribute decision making (MADM) methodology and consists of elimination search and technique for order preference by similarity to ideal solution (TOPSIS) approach. Authors have suggested a coding scheme based on 190 pertinent attributes for a given thermal power plant for the development of a large database of available plants, and their subsequent retrieval. The "technique for order preference by similarity to ideal solution" (TOPSIS) approach has provided a complete and thorough comparison and ranking of available power plants. Authors have also developed a user friendly computer software for Elimination Search and TOPSIS approach.

C. Phaneendra Kiran et al. (2011) presented a methodology useful in optimal selection of a mechatronic system based on the Mutli Attribute Decision Making (MADM) approach. Authors contributed in this paper by proposing a coding scheme which is a collection of 88 attributes which characterize a mechatronic system and is useful in differentiating mechatronic system alternatives. An illustrative example of selecting a hard disk drive (HDD), a mechatronic system, for the up-gradation of constumer's office desktops is given to explain the methodology. Authors also identified 3-stage selection procedure, which includes elimination search, TOPSIS based evaluation and ranking, other graphical methods (linear graph and spider diagram), works on the information of the pertinent attributes. This procedure ranks the mechatronic system alternatives based on the Euclidian distance of alternatives from hypothetically best and hypothetically worst mechatronic systems.

2.3 Gap Analysis

From the literature review, it is seen that a lot work has been done on various aspects of agile manufacturing systems such as design, planning, scheduling and modeling under varying conditions. It is observed that the main application is in the field of selection of decision models for agile manufacturing system in order to reduce time and cost involved in the procedure, however, the cost of incorporating these decision models is still high. Many of the components of agile manufacturing systems have been considered individually but none of the researchers have considered all these components in a unified manner. Also the subsystems are considered independently in design or modeling of and agile manufacturing system without considering the effect of other subsystems as well as the interaction between them. Only a few researchers have considered the various subsystems simultaneously in evaluation and optimum selection of agile manufacturing systems. In actual, modeling, selection and evaluation of agile manufacturing system depends on many attributes. It is therefore reasonable to consider more factors. An exhaustive list of attributes for agile manufacturing is not available in the literature. Also, from the literature review, it can be seen that no one has considered the structural constituents for analyzing an agile manufacturing system along with their interactions at conceptual and design stages and there is no methodology proposed for an integrated system approach for analyzing agile manufacturing systems.

From the literature review regarding system approach, it can be seen that the desired methodologies for optimum selection and for analyzing agile manufacturing systems, though seen in other engineering areas, have not been developed for agile manufacturing systems. So there is a need to develop such methodologies and it is hoped that the system approach is a useful tool and technique.

CHAPTER 3
STRUCTURAL MODELING AND ANALYSIS OF AGILE MANUFACTURING SYSTEM

3.1 Introduction

Agility refers to the ability of a system to rapidly respond to change by adapting its initial stable configuration (A. Wieland & C.M. Wallenburg, 2012). This study is beneficial in obtaining system wide optimised solutions and to increase the level of comprehensiveness of the agile manufacturing system modeling and to develop method of characterization based on the structure of the agile manufacturing system. The main goal of agile manufacturing is to quickly produce small batch lots economically, with least response time possible. This is achieved by integration of information technology in machine control and production planning and decision making skills for faster flow of information among various departments. The main characteristics of agile manufacturing are re-configurability, scalability and reusability. With the power (i.e. variety of products to choose from) to the customer in today's market, the need for agile manufacturing is immense which is why it is very important for organisations to adopt the principles of agile manufacturing to survive in competitive environment today.

A comprehensive literature on agile manufacturing systems suggests that the key issue to be addressed by the manufacturing enterprises is to rapidly and cost-effectively satisfy the various dynamic demands of the market and to adapt to the unpredictable changing environment and increasing rates of new product introduction. This is achieved by adopting the dynamic data interchange scheme (C.K.M. Lee et al., 2004) and control strategies (M.K. Lim & Z. Zhang, 2004) to maximize responsiveness using multi-agents for integrating design, process planning and production scheduling (Wang et al., 2002; Y.H. Wang et al., 2003; M.C. Palacios et al., 2006; Y. Tanimizu et al., 2006). Production scheduling has also been achieved by using genetic algorithms in the agile manufacturing environment (L.K. Gaafar et al., 2008; A.D. Yimer & Kudret Demirli, 2010). The mechanism for various agents includes factors such as functionality, capability, status, capacity and physical relationships and interactions between agents. A need for agility in today's competition has been recognised in a manufacturing system where concepts of MRP, TQM and JIT have already been implemented (A.C. Yao, J.G.H. Carlson, 2003; R.A. Inman et al., 2011). The automotive industry is also integrating the concepts of agile manufacturing due to ever changing customer demands and turbulent market conditions (D.A. Elkins et al., 2004) which permit fast and cost-effective responses to support rapid product launches for previously unplanned products. Vendor selection (W.H. Ip et al., 2004; M.A. Vonderembse et al., 2006) and partner selection (Naiqi Wu & Ping Su, 2005) in agile manufacturing environment is an important consideration in the agile manufacturing environment as material requirements are never constant and agility can be realized by a dynamically reconfigurable virtual enterprise. Also, the impact of alignment between virtual enterprise and information technology on business performance in an agile manufacturing environment has also been studied in the past (Qing Cao & Shad Dowlatshahi, 2005). Product life cycle in agile manufacturing is typically short which requires a framework for designing supply chains (M.A. Vonderembse et al., 2006; N. Costantino et al., 2012). In order to achieve agility in a manufacturing system, team-based work is very necessary while using balance theory as a framework (Charlene A. Yauch, 2007). In turbulent environments, the integrated use of agile manufacturing practices promotes manufacturing competitive strength, leading to better operational, market and financial performance (D.V. Bustelo et al., 2007). In recent years, agile manufacturing has attracted considerable attention as an emerging concept in the industry, combining virtual manufacturing cells to construct new manufacturing systems to respond to the changing market needs, especially in nonlinear processes (R.Y.K. Fung et al., 2008). Holonic manufacturing systems have proposed solutions to reconfigurability and evolvability issues of manufacturing control systems in an agile environment (Pascal Blanc et al., 2008). For responding to the mass customization trend it is necessary to develop an agility-based manufacturing system to catch on the traits involved in MC (Wen-Pai Wang, 2009; Mert Bal & Majid Hashemipour, 2009) and also based on the characteristics of mass customization (MC) product manufacturing and the requirement of agile manufacturing, an MC product manufacturing agility evaluation index system is established (S.L. Yang & T.F. Li, 2002). Recently, the build-to-order (BTO) manufacturing strategy is becoming a popular operation strategy to achieve agility as well as leanness in a mass-scale customization process (A.D. Yimer & Kudret Demirli, 2010). The rapid growth of the Internet and the expansion of electronic commerce applications in manufacturing have given rise to electronic customer relationship management (e-CRM) which enhances the overall customer satisfaction (Faramak Zandi & Majid Tavana, 2011). Agility is widely accepted in the manufacturing industry as a new competitive concept and a numerical taxonomy of how to develop a manufacturing strategy based around agility has been developed in the past (D.Z. Zhang, 2011). The concept of agile manufacturing has also been applied in various industrial processes such as specialty chemical industries and water reuse network design (A. Guisinger & B. Ghorashi, 2004; Jie Fu et al., 2012). A core issue faced within agile manufacturing is the need for appropriate and supporting production and operations systems. Many design dimensions of agility and agile manufacturing exist. To help attain this goal for integrating the many design dimensions, operations infrastructure and capacity (A.M. Uribe et al., 2003) must be carefully planned to manage production flow, and thus production layout planning takes on an increasingly important role (M.A. Hasan et al., 2012). The issue of quality of products has been addressed by various researchers in the past by introduction of sequential process control and orthogonal array based experimentation (H.E. David & Arsen Grigoryan, 2002; S.R. Devadasan et al., 2005).

Although a lot of work has been done in the field of agile manufacturing, there is no such work that integrates the whole system so as to make use of inter-relationships and interactions of various subsystems of the entire agile manufacturing system in order to produce high quality products economically and with highest responsiveness possible. For this objective to be fulfilled, a graph theory based model is proposed which divides the agile manufacturing system into subsystems and further up to component level, making use of various interactions in the system. These kinds of models have already been applied extensively to analyze other complex engineering systems such as mechatronic system (C.P. Kiran et al., 2011). The proposed model will be useful for analyzing, evaluating and designing an agile manufacturing system at the conceptual stage.

3.2 Identification of attributes and subsystems of the agile manufacturing system

For development of the methodology, five subsystems have been identified namely input, management, manufacturing process, support and output subsystems. This is a representative assumption for a general agile manufacturing system and all the important criteria governing the agile manufacturing system behaviour are reflected in these subsystems. These subsystems may not be universal and there may be some variations for modeling specific agile manufacturing systems. However, the proposed model has the capability to consider any such variation and is suitable for modeling any particular agile manufacturing system structure. The following sections discuss the composition, scope and importance of each of the identified subsystems of the manufacturing system.

3.2.1 Identification of subsystems

An attempt is made to consider all the aspects which affect performance of agile manufacturing system and group these aspects in five subsystems.

3.2.1.1 Agile Input Subsystem

The input subsystem includes factors such as material, capital, business environment, design engineering and suppliers. The material quality directly influences properties of the finished product, thereby influencing the overall competitiveness of the manufacturing system to a great extent. The capital involved in the organisation would directly reflect on its brand image. The business environment provides an integrated decision platform for agile design, selection and optimisation of materials for a changing demand. Supplier's relations and selection is an important deciding factor in the overall competitive position of a manufacturing system.

3.2.1.2 Agile Management Subsystem

The management subsystem is one of the main subsystem that decides the position of the manufacturing system in the global market. It performs functions such as strategy formulation for the ever changing market environment, production planning & control, monitors performance of employees in manufacturing departments as well as in other departments, establishes standard working techniques for each and every operation, maintains overall quality of products manufactured. The management subsystem also performs the task of feedback from various levels of employees for taking corrective actions in order to increase productivity.

The above five subsystems are expected to represent the total agile manufacturing system.

3.2.1.3 Agile Manufacturing Process Subsystem

The manufacturing subsystem includes factors such as machines & equipments, operational flexibility, machinery utilization, compatible human skill, material handling systems, safety & facility to workers. The role of manufacturing subsystem in providing an edge to an organisation in the global market is immense as this subsystem deals with latest methods and practices' implementation in producing high end products of various types. The varying product mix produced by the manufacturer is a result of combination of modern machinery, tools and techniques and compatible human skill. Apart from the skill of workers, another important consideration is their behaviour (attitude) which distinguishes good companies from world class companies.

3.2.1.4 Agile Support Subsystem

The support subsystem works as an interface between various departments of an organisation for communication of orders, work related issues, production schedules, timely dispatch of finished goods etc. It acts as a lifeline of the total manufacturing subsystem as fresh instructions which change often in an agile manufacturing environment are directly communicated through this subsystem. Most of the communication is shared between inventories, sales, demand forecast, order status and production schedules. The support subsystem is also responsible for timely maintenance of machinery & equipment for high productivity and reliability. Poor maintenance would result in increased downtimes and an unreliable manufacturing environment. Other functions of the support subsystem include accounting and finance which are responsible for keeping record of all the activities in the organisation and allocating funds for various activities respectively.

3.2.1.5 Agile Output Subsystem

The output subsystem performs the function of sales & distribution of finished products, waste disposal, obtains feedback from customers using various methods and helps in maintaining the image of the organisation in the world market. In an agile manufacturing environment, the most important task of the output subsystem is to predict changes in the market before the competitors and responding to customer needs.

3.2.2 Total agile manufacturing system

Five subsystems as identified above constitute the total agile manufacturing system. The tasks for each subsystem and the sub-subsystem have been compiled in the tree diagram at total manufacturing system level in Figure 3.1 Each subsystem consists of attributes of agile manufacturing system which help in better and in-depth understanding of the total agile manufacturing process as well as the system.

Each subsystem and its component is responsible for a better total agile manufacturing system in its own way. For example, the design engineering component of the input subsystem helps in achieving the characteristics of reusability and scalability of previous designs with a little tweaking in the original design files. This would result in generation of a new part program for manufacturing the product in quicker time than usual. Again the concept of re-configurability in the equipment subsystem would reduce time required to produce the product. In this way many variants of a single product can be produced quickly and economically with maximum responsiveness, reducing the lead time to market.

In many organisations today, the design, production planning and production scheduling components are integrated which implies that new products can be introduced in the agile manufacturing system at a faster rate without delaying the production. So the organisation would prosper in a dynamic market with high competition.

Integration of the subsystems and their components is very necessary for smooth operation and minimizing any kind of wasteful activity in the total agile manufacturing system. Wasteful activity refers to any activity in the system which consumes resources but does not add any value to the product or process. There are mainly eight activities which are identified as wasteful, namely; motion, waiting, defects, transport, overproduction, inventory, process and people (Bill Ray et al., 2006). In other words, a manufacturing system can become agile if it becomes lean too.

Another point to be kept in mind is that any number of subsystems can be taken for the agile manufacturing system. In this research, five subsystems are taken just to explain the graph theoretic modeling methodology.

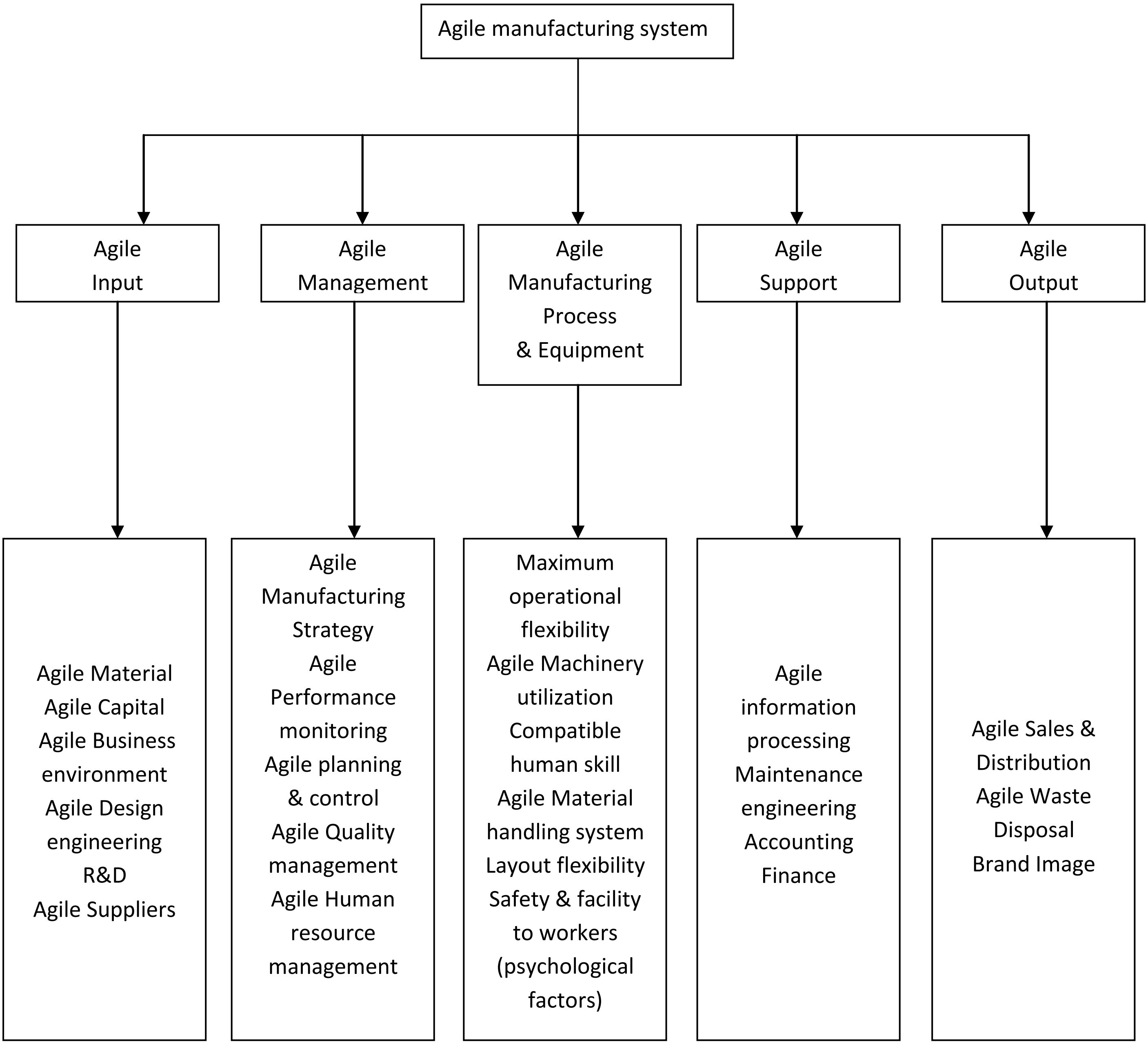

Figure 3.1 Agile manufacturing system tree diagram.

3.2.3 Interactions between subsystems and integrative agile manufacturing system

The subsystems in agile manufacturing system are interrelated and interdependent on each other in many ways for example the quality of output product depends upon the human skill (management), the manufacturing process, as well as the quality of raw material (input) used for its production. Overall performance of agile manufacturing system depends upon integrative functioning, decision making and implementation.

Although the tree diagram in figure 3.1 clearly represents all the subsystems of agile manufacturing system, it fails to represent the interdependencies and connectivity between different subsystems which is shown by a schematic diagram in figure 3.2 This diagram is helpful in explaining the methodology. The model is flexible enough but general in nature and a customized model can be derived from the generic method.

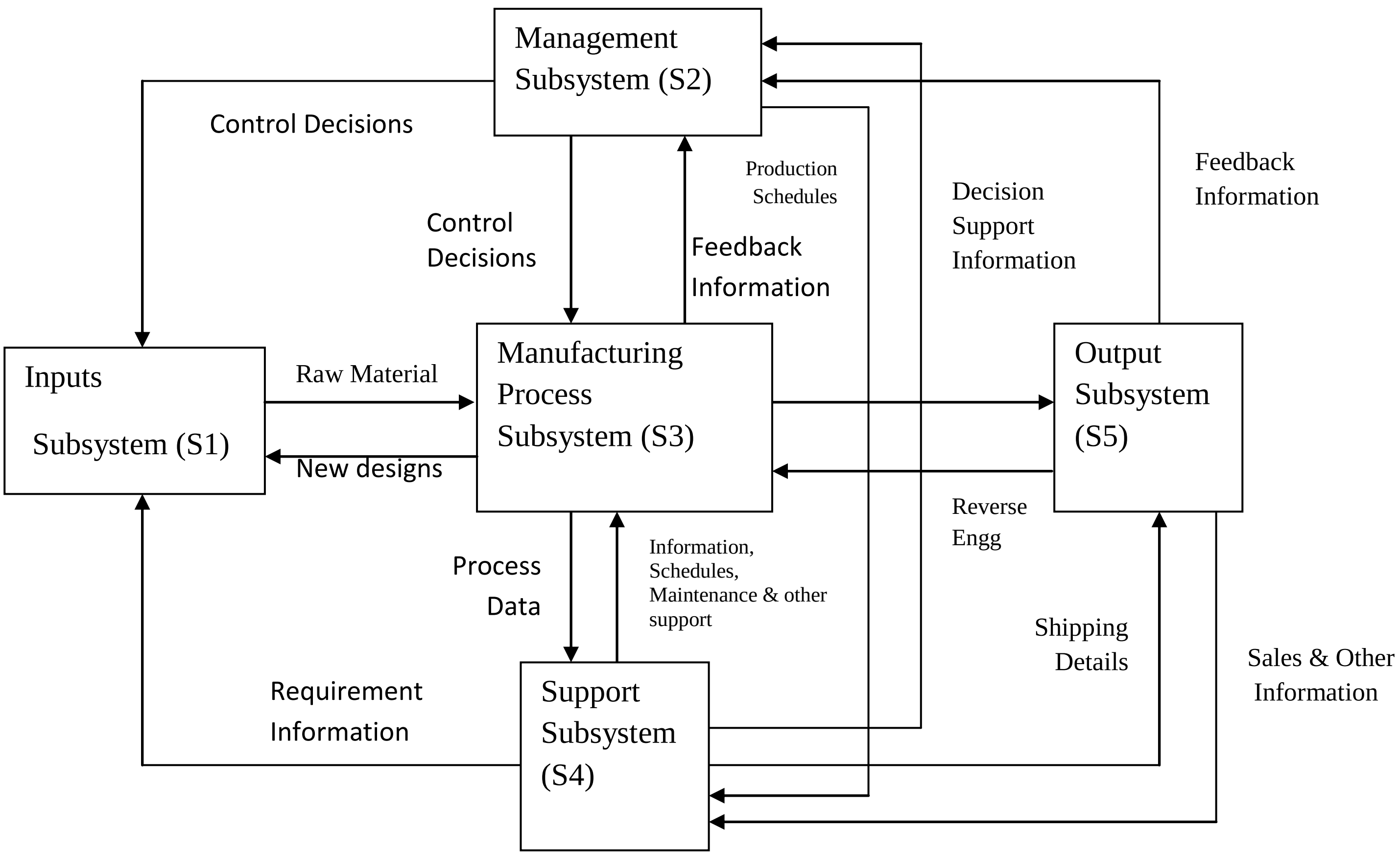

Figure 3.2 Schematic diagram of integrative agile manufacturing system.

The manufacturing process subsystem is directly influenced by the inputs subsystem as factors such as supplier relationship (quality and reliability) help in smooth running of the manufacturing process.

The output subsystem is directly dependent upon the manufacturing subsystem but the manufacturing process is not dependent on the output. Rather the output influences the manufacturing process subsystem indirectly through a loop of information processing function in the support subsystem and then to the management subsystem in terms of providing processed information. The management subsystem takes control decisions for the manufacturing process and finally the manufacturing process satisfies the new output requirements, thus completing the loop of information flow. For example, the management subsystem controls the input decisions based upon feedback from output (sales forecast) and support (customer feedback, maintenance schedules etc.) for a new product introduction in the market. With the introduction of reverse engineering techniques due to high global competition, the products can be directly manufactured without any design details. This means that the output subsystem directly influences the manufacturing subsystem. And so there is a direct link between manufacturing process subsystem and inputs subsystem as new design details will now be directly fed by the manufacturing process.

Information about sales from the output subsystem and other subsystems such as manufacturing subsystem is collected and processed by support subsystem and then provided to the management subsystem. Therefore, there exists a link between output to the support subsystem and the management subsystem which again controls production planning control system and thus controls the manufacturing process subsystem and finally the desired output is attained through these links.

The loop links of interactions represent the typical function of the management subsystem i.e. obtaining feedback from the output subsystem and then controlling the manufacturing process to produce better products for the output subsystem through various means and procedures. Similarly, the support subsystem assists the manufacturing process subsystem by providing useful processed information such as the schedules received from the management subsystem for performing various tasks and provides information to supplier for arranging the necessary materials according to the requirements. The management and control subsystem also collects performance reports about various components of manufacturing process subsystem (such as humans, equipments, etc.) as well as from other subsystems of input and support. These findings show that the overall functioning of the manufacturing system is dependent on its structural design. The practices followed in the operation of subsystems and in the interactions between these subsystems set one manufacturing enterprise apart from the other and the authors consider that it is the cause for their success or failure.

3.2.4 Assumptions for developing graph theoretic model

The proposed graph theoretic model for manufacturing systems is based on some assumptions as listed below:

- There is a co-relation between the performance of the agile manufacturing system and its structure, *for example*, productivity, quality, reliability, etc. This co-relation is quantitative in nature.
- The structure of the agile manufacturing system, its subsystems and their interactions can change from organisation to organisation i.e. there is no fixed rule for obtaining the structure of an agile manufacturing system. These would rather depend upon the organisation's aims and objectives, value system and business strategy.
- Complete information (related to a real life situation) of any agile manufacturing system can be stored in a variable permanent matrix by associating a vector of attributes representing subsystems (i.e. diagonal elements) and interconnections (i.e. off-diagonal elements). Identification of these attributes would help in representing the agile manufacturing system completely.
- Since the structure of agile manufacturing system depends upon the organisation, the permanent function of the variable permanent matrix characterises each agile manufacturing system uniquely.
- Individual performance of subsystems, sub-subsystems and their components along with interactions/interdependences/influences between them would affect the overall performance of the agile manufacturing system.
- The modeling/methodology used is based on bottom up approach i.e. permanent values of sub-subsystems are used in permanent matrices of subsystems and permanent function values of subsystems are used to calculate permanent function of overall agile manufacturing system.
- The numerical values for interactions between subsystems can be assigned by experts.

3.3 Graph theoretic model of the manufacturing system

The graph theoretic approach is computer friendly, easy to understand and flexible which is why it finds use in a wide range of real life situations in today's world. Since figure 3.1 and 3.2 are non mathematical representations of the agile manufacturing system, they cannot be used for analysis of the structure. So, a mathematical representation of various subsystems and their interactions are shown by system graph in figure 3.3 This helps in manipulation of the structure of the agile manufacturing system in a systematic way to obtain the desired results. Moreover, the mathematical representation can be connected to other mathematical models other than the graph theoretic model.

From figure 3.3, the vertices S_1, S_2, S_3, S_4 and S_5 represent various subsystems and the interaction between these subsystems is represented by e_{ij}. e_{ij} signifies influence of the i^{th} subsystem on the j^{th} subsystem.

Let us define a linear graph G as a function of vertex set and edge set as G = *f*(S,E) where S represents the set of vertices, S = $\{S_1,S_2,....,S_n\}$ and E represents the set of edges E = $\{e_{12},e_{23},...,e_{mn}\}$ connecting different vertices.

It has to be noted that the arrow head represents dependence of the subsystem from which it is directed to the subsystem to which it is directed while the reverse is not true ($e_{ij} \neq e_{ji}$).

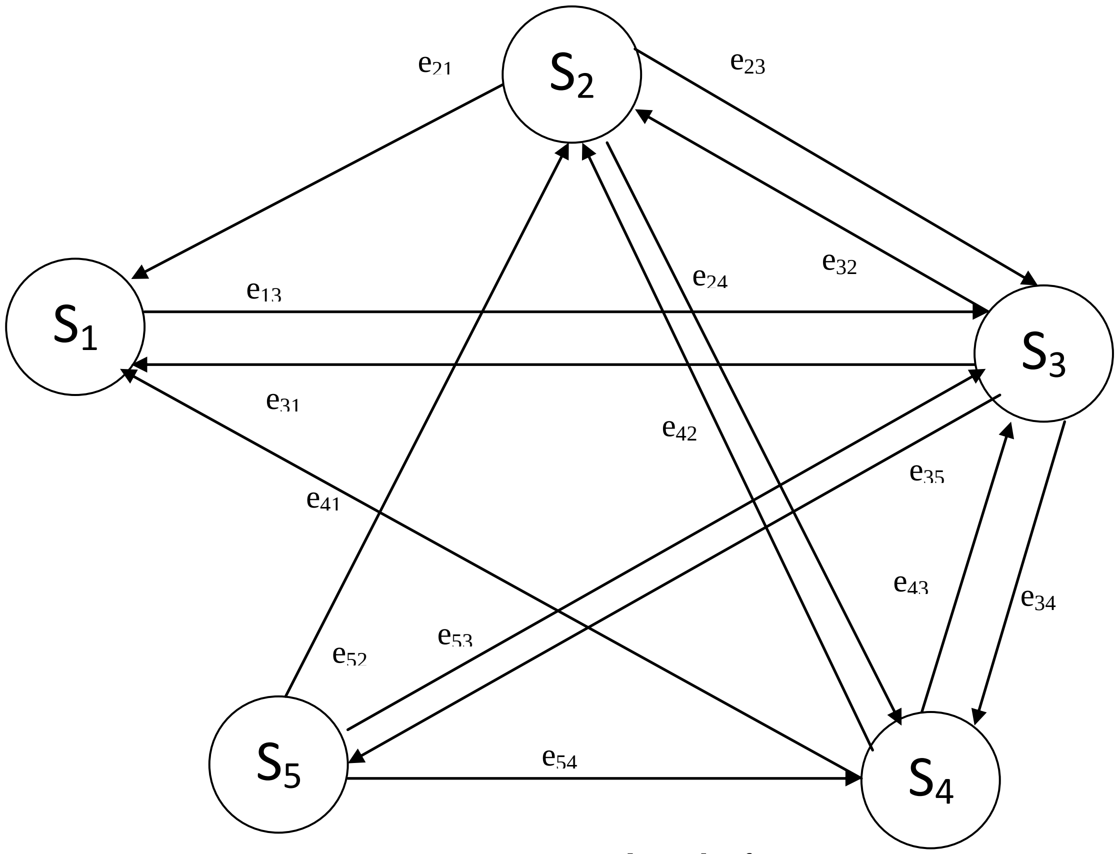

Figure 3.3 Structural graph of agile manufacturing system

3.3.1 Nomenclature

G = manufacturing system graph

V = set of vertices

E = set of edges

S_1 = input subsystem

S_2 = management subsystem

S_3 = manufacturing process subsystem

S_4 = support subsystem

S_5 = output subsystem

e_{ij} = influence/interaction of subsystem S_i to subsystem S_j

L_{ijk} = interaction loop among subsystems S_i, S_j and S_k

J_{kl} = number of elements in the I^{th} subgroup of the k^{th} group in the permanent multinomial

A = manufacturing system adjacency matrix

B = manufacturing system characteristic matrix

C = manufacturing subsystem characteristic and interaction variable matrix

D = manufacturing subsystem characteristic diagonal matrix

E = interaction variable matrix

P = manufacturing subsystem permanent matrix

PS_1 = permanent matrix for input subsystem structure

PS_2 = permanent matrix for management subsystem structure

PS_3 = permanent matrix for manufacturing process subsystem structure

PS_4 = permanent matrix for support subsystem structure

PS_5 = permanent matrix for output subsystem structure

3.3.2 Matrix representation for the agile manufacturing system graph

The matrix representation of the agile manufacturing system graph helps in better control over the entire system. In order to represent the graph in matrix form, we make use of adjacency matrix which is a square matrix.

Adjacency matrix of the graph with five nodes will be a five order binary (0, 1) square matrix, A = $[a_{ij}]$ such that:

$$a_{ij} = \begin{cases} 1, \text{if subsystem i has an influence on subsystem j} \\ \qquad 0, \text{if i and j are not connected} \end{cases}$$

Thus the adjacency matrix A for the agile manufacturing system graph, G is written as below:

$$A = \begin{array}{cc} & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \quad \text{Subsystems} \\ & \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad (3.1)$$

3.3.2.1 Agile manufacturing system characteristic matrix

The adjacency matrix A is representing only the interrelationships between subsystems, while the manufacturing system characteristics are not represented. Hence, another matrix B similar to characteristic matrix is derived and is named as agile manufacturing system characteristic matrix, B as below in equation (3.2):

$$B = [\lambda I - A] = \begin{array}{cc} & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \quad \text{Subsystems} \\ & \begin{bmatrix} \lambda & 0 & -1 & 0 & 0 \\ -1 & \lambda & -1 & -1 & 0 \\ -1 & -1 & \lambda & -1 & -1 \\ -1 & -1 & -1 & \lambda & 0 \\ 0 & -1 & -1 & -1 & \lambda \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad (3.2)$$

where λ represents eigen values for the matrix; I is the identity matrix of same order as A.

As the common matrix operations allow the rows as well as columns to change positions without affecting the value of the matrix, a matrix cannot be considered as an invariant and thus not a unique representation of the interactions or the manufacturing system characteristics. The determinant of the manufacturing system characteristic matrix B will yield an invariant of this matrix and is developed as in equation (3.2) given below:

$$\text{Det (B)} = \lambda^5 + 7\lambda^3 + 4\lambda^2 + 4\lambda + 2 \qquad (3.3)$$

As this characteristic polynomial is an invariant for the agile manufacturing system characteristic matrix, it forms the basis for characterizing the agile manufacturing system information uniquely. But, as there is no distinction between different subsystems as well as the levels of interactions between them, it cannot be used to characterize the agile manufacturing system completely.

3.3.2.2 Agile manufacturing system characteristic and interdependence variable matrix

To overcome the limitation of non-discrete representation of the subsystems of agile manufacturing system and the variable level of interactions in the subsystems in the matrix B, another matrix C, called as agile manufacturing subsystem characteristic and interdependence variable matrix (AMSSCIVM), is developed as below in equation (3.4). For this purpose, a five order square matrix E with off-diagonal elements e_{ij} representing varying levels of interactions between the subsystems is defined. Another matrix D, a diagonal matrix with diagonal elements representing five different subsystems is defined. The matrix C can be developed from the matrices E and D as below:

$$C = [D - E] = \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \;\text{Subsystems} \\ \begin{bmatrix} S_1 & 0 & -e_{13} & 0 & 0 \\ -e_{21} & S_2 & -e_{23} & -e_{24} & 0 \\ -e_{31} & -e_{32} & S_3 & -e_{34} & -e_{35} \\ -e_{41} & -e_{42} & -e_{43} & S_4 & 0 \\ 0 & -e_{52} & -e_{53} & -e_{54} & S_5 \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \qquad (3.4)$$

This matrix distinctly represents characteristic features of the subsystems and their interactions. Thus, the matrix C in equation (3.4) is complete structural representation of the manufacturing system capturing all the data related to the agile manufacturing system including the interactions. But, as discussed in the previous subsection, it does not represent the agile manufacturing system uniquely. The determinant of matrix C is an invariant of the manufacturing system as discussed in the previous subsection and is developed as in equation (3.5) below. It is given the name of agile manufacturing system characteristic and interdependence variable multinomial.

$$\begin{aligned} Det(C) = {} & S_1S_2e_{35}e_{43}e_{54} + S_1S_2S_4e_{35}e_{53} + S_1e_{23}e_{35}e_{42}e_{54} + S_1S_3S_5e_{24}e_{42} + S_1S_4e_{23}e_{35}e_{52} - \\ & S_1e_{24}e_{35}e_{42}e_{53} - S_1e_{24}e_{35}e_{43}e_{52} - S_1S_2S_3S_4S_5 + S_1S_2S_5e_{34}e_{43} + S_1S_4S_5e_{23}e_{32} + \\ & S_1S_5e_{23}e_{34}e_{42} + S_1S_5e_{24}e_{32}e_{43} - e_{13}e_{21}e_{35}e_{42}e_{54} - S_4e_{13}e_{21}e_{35}e_{52} - S_2e_{13}e_{35}e_{41}e_{54} - \\ & e_{13}e_{24}e_{35}e_{41}e_{52} - S_4S_5e_{13}e_{21}e_{32} - S_5e_{13}e_{21}e_{34}e_{42} - S_2S_4S_5e_{13}e_{31} - S_2S_5e_{13}e_{34}e_{41} + \\ & S_5e_{13}e_{24}e_{31}e_{42} - S_5e_{31}e_{24}e_{32}e_{41} \qquad (3.5) \end{aligned}$$

The terms in multinomial of equation (3.5) can be rearranged in decreasing order of subsystem characteristic terms S_i's. Further the five subsystem matrix may be classified into six groups and is shown in equation (3.6a):

$Det(C) = [–S_1S_2S_3S_4S_5] + [–S_2S_4S_5e_{13}e_{31} + S_1S_2S_4e_{35}e_{53} + S_1S_2S_5e_{34}e_{43} + S_1S_3S_5e_{24}e_{42} + S_1S_4S_5e_{23}e_{32}] + [–S_2S_5e_{13}e_{34}e_{41} – S_4S_5e_{13}e_{21}e_{32} + S_1S_2e_{35}e_{43}e_{54} + S_1S_4e_{23}e_{35}e_{52} + S_1S_5e_{23}e_{34}e_{42} + S_1S_5e_{24}e_{32}e_{43} + [\{S_1e_{23}e_{35}e_{42}e_{54} + S_5e_{13}e_{24}e_{31}e_{42}\} + \{–S_1e_{24}e_{35}e_{42}e_{53} – S_1e_{24}e_{35}e_{43}e_{52} – S_2e_{13}e_{35}e_{41}e_{54} – S_4e_{13}e_{21}e_{35}e_{52} – S_5e_{13}e_{21}e_{34}e_{42} – S_5e_{31}e_{24}e_{32}e_{41}\}] + [– e_{13}e_{21}e_{35}e_{42}e_{54} – e_{13}e_{24}e_{35}e_{41}e_{52}].$ (3.6a)

The loops and dyads (interaction loop between two subsystems) in equation (3.6a) are written in a more convenient way in equation (3.6b). Here, the dyad (two subsystem loop) between subsystem S_i and S_j is represented as a loop L_{ij} in place of e_{ij} and e_{ji}. A loop between subsystems S_i, S_j and S_k, i.e. $e_{ij}e_{jk}e_{ki}$ has been represented as L_{ijk} and for the reverse loop of $e_{ji}e_{ik}e_{kj}$ as L_{jik}. The loops $e_{ij}e_{jk}e_{kl}e_{li}$, and $e_{ij}e_{jk}e_{kl}e_{lm}$, e_{mi} are represented by L_{ijkl} and L_{ijklm}, respectively. Thus, equation (6a) has been rewritten as below:

$Det(C) = [–S_1S_2S_3S_4S_5] + [–S_2S_4S_5L_{13} + S_1S_2S_4L_{35} + S_1S_2S_5L_{34} + S_1S_3S_5L_{24} + S_1S_4S_5L_{23} + [–S_2S_5L_{134} – S_4S_5L_{132} + S_1S_2L_{354} + S_1S_4L_{235} + S_1S_5L_{234} + S_1S_5L_{243} + [\{S_1L_{2354} + S_5L_{13}L_{24}\} + \{–S_1L_{24}L_{35} – S_1L_{2435}– S_2L_{1354} – S_4L_{1352} – S_5L_{1342} – S_5L_{2413}\}] + [– L_{13542} – L_{13524}].$ (3.6b)

The multinomial (3.6b) models a general agile manufacturing system conclusively and is a useful tool for analyzing and decision making but has some limitation which is why permanent function is suggested.

3.3.3 Composite performance index and the permanent function

Permanent matrix and permanent function are generally used to study combinations of discrete structure as they contain only positive signs. This ensures retention of complete structural and performance information.

The permanent of a n x n matrix $Z = (z_{i,j})$ is defined as

$$Per (Z) = \sum_{\sigma \epsilon S_n} \prod_{i=1}^{n} Z_{i,\sigma(i)}$$

A composite score of the agile manufacturing system in a performance dimension maybe helpful in analysing the total performance and one of the ways to obtain it is by using appropriate numerical values for the manufacturing system variables in equations (3.6a) or (3.6b). But in such a case, some structural information of the agile manufacturing system is likely to be deleted because of many subtraction operations. In order to overcome this limitation, the use of permanent matrix and the permanent function is proposed.

3.3.3.1 The manufacturing system permanent matrix

The permanent matrix is obtained when the negative sign from all the elements in AMSSCIVM in equation (3.4) are converted into positive. The permanent matrix thus developed is called agile manufacturing system characteristic and interdependence variable permanent matrix (AMSPM) and is shown below as matrix P:

$$\begin{array}{cc} & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \quad \text{Subsystems} \\ P = & \begin{bmatrix} S_1 & 0 & e_{13} & 0 & 0 \\ e_{21} & S_2 & e_{23} & e_{24} & 0 \\ e_{31} & e_{32} & S_3 & e_{34} & e_{35} \\ e_{41} & e_{42} & e_{43} & S_4 & 0 \\ 0 & e_{52} & e_{53} & e_{54} & S_5 \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} \end{array} \quad (3.7)$$

3.3.3.2 Manufacturing system characteristic and interdependence variable permanent function

The permanent function of the matrix P in equation (3.7) has been developed in equation (3.8). The permanent function, Per(P) is same as the multinomial, Det(C) in equation (3.6b) apart from the fact that only the signs of some of the terms are different. Number and the type of terms in the two multinomials are exactly the same. Procedure for deriving Det(C) and Per(P) from the respective matrices is same except no negative signs appearing in Per(P) at any stage of its calculation. Thus, permanent function model is a unique and complete structural representation of the agile manufacturing system with the added advantage of using numerical values of each term without any chance of losing important information in the total numerical index:

$$\text{Per(P)} = [S_1S_2S_3S_4S_5] + [S_2S_4S_5L_{13} + S_1S_2S_4L_{35} + S_1S_2S_5L_{34} + S_1S_3S_5L_{24} + S_1S_4S_5L_{23} + [S_2S_5L_{134} + S_4S_5L_{132} + S_1S_2L_{354} + S_1S_4L_{235} + S_1S_5L_{234} + S_1S_5L_{243} + [\{S_1L_{24}L_{35} + S_5L_{13}L_{24}\} + \{S_1L_{2354} + S_1L_{2435} + S_2L_{1354} + S_4L_{1352} + S_5L_{1342} + S_5L_{2413}\}] + [L_{13542} + L_{13524}]. \quad (3.8)$$

Equation (3.8) can represent not only most general agile manufacturing system, but any customized/specific study related to structure, quality, responsiveness etc. can be made. The numerical index is developed based on the permanent multinomial terms in equation (3.8), by assigning numerical value to individual structural elements can be considered a composite score of the total agile manufacturing system in any performance dimension depending upon the person selected for giving values to individual structural elements. This score can prove as a powerful tool for comparison, ranking of different agile manufacturing system designs and optimum selection of agile manufacturing system structure. Thus, the permanent function is proposed as a complete tool for the total structural analysis of the agile manufacturing system.

3.3.3.3 Assigning the numerical values

The people working in respective areas of an agile manufacturing system are the ones who understand the system behaviour closely and are best suited to draw useful and meaningful insights. The numerical values to various subsystems as well as the interactions therein may be assigned by them depending on the levels of performance in the dimension chosen for analysis. For example, the dimension may be efficiency, reliability, re-configurability or effectiveness. Other performance parameters may be material removal rate (mrr), surface roughness, depth of cut etc. Thus, a mechanism is formulated so that the knowledge of various experts is systematically used and combined to obtain a single numerical score. For large and complex subsystems, the numerical values may be assigned by decomposing the subsystems into further smaller component units and their permanent function would then be used as the numerical score for the subsystem. Thus, the numerical values for each subsystem variables S_1, S_2, S_3, S_4 and S_5 may be obtained as below:

$S_1 = Per(PS_1)$; $S_2 = Per(PS_2)$; $S_3 = Per(PS_3)$; $S_4 = Per(PS_4)$; $S_4 = Per(PS_5)$; where PS_1, PS_2, PS_3, PS_4, PS_5 are the variable permanent matrices for five subsystems.

Thus, the methodology can be applied in a bottom-up approach i.e. the analysis begins from the lowest level and proceeds to the total agile manufacturing system level hence; we can obtain the complete structural evaluation of the agile manufacturing system as a single index.

3.3.4 Structural analysis of agile manufacturing system

The permanent multinomial in equation (3.8) consists of structural elements i.e. subsystem characteristics (S_i's) and structural interactions (e_{ij}'s). The existence of elements such as $e_{ij}e_{ji}$, $e_{ij}e_{jk}e_{ki}$, $e_{ij}e_{jk}e_{kl}e_{li}$, $e_{ij}e_{jk}e_{kl}e_{lm}$, e_{mi} in the multinomial terms indicate that the subsystems are interacting in the form of a dyad, three subsystem, four subsystem and five subsystem loops. These terms represent the real subsets of the agile manufacturing system structure. The terms in each group of the multinomial form a separate set, which characterizes the manufacturing system uniquely. These real subsets of the total manufacturing system identified from equation (3.8) shown as sub-graphs as in Figure 3.4. These sub-graphs represent the subsystems of the agile manufacturing systems interacting in various ways and thus helping achieve varied goals of the agile manufacturing system by critical analysis of alternate solutions for optimum decisions. Equation (3.8) contains 22 terms. As each of the equation represents a physical system which is a subsystem of the complete system shown in figure 3.2 so the multinomial is a combination of all possible real solutions which are derived from the analysis of these terms.

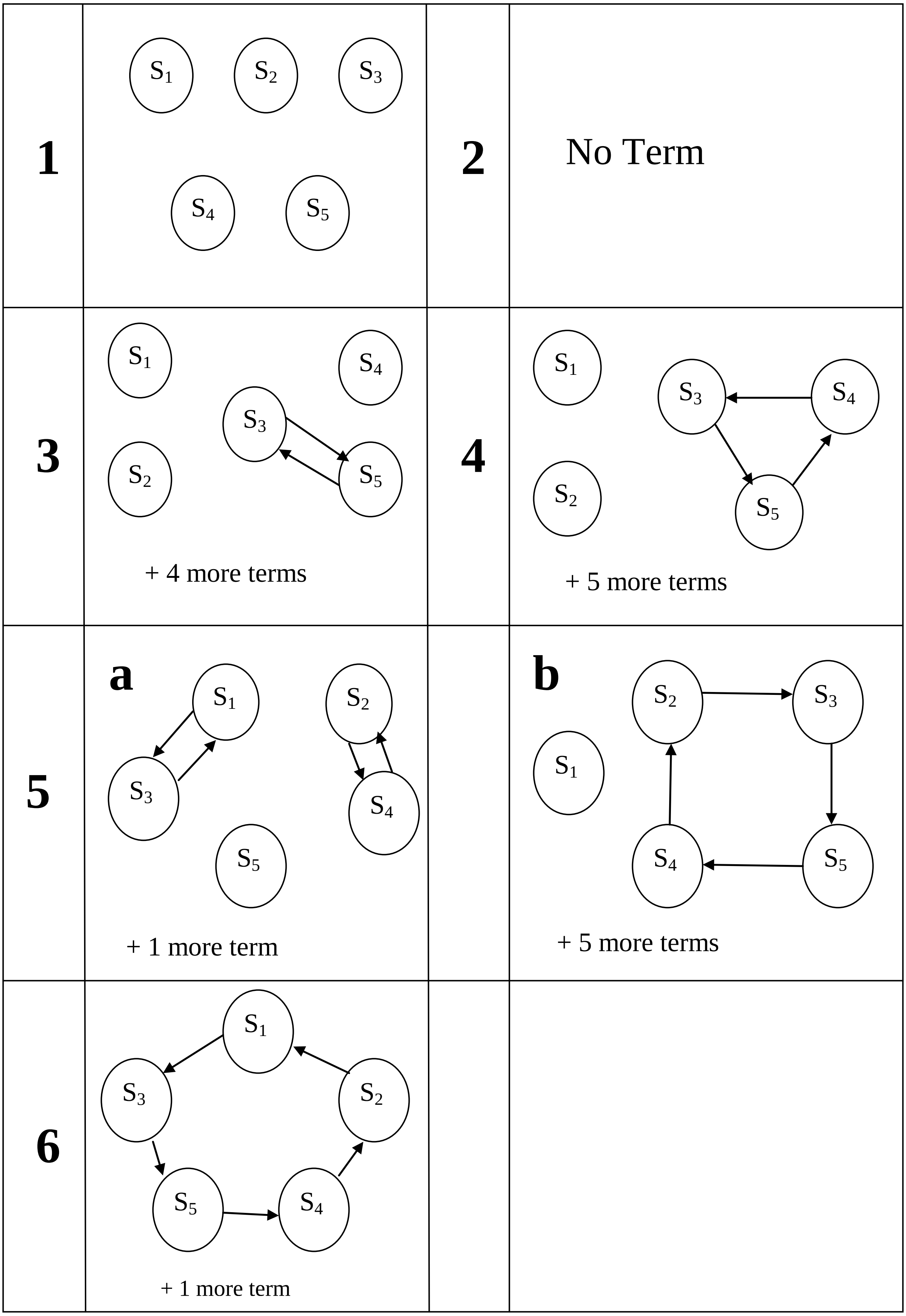

Figure 3.4 Graphical representation of the permanent multinomial

Example 1

The term ($S_2S_4S_5L_{13}$) of the third subgroup in the characteristic polynomial may be interpreted as that corresponding to the use of reverse engineering practices in the manufacturing system. For example, a new product is launched in the market by a competitor for which no design details or specifications are present. The use of reverse engineering techniques would help in examining the product and also improvements to that product can be made, resulting in a better product than that of the competitor. The product is examined to form design and manufacturing inputs for mass production. The output subsystem provides the product and the management subsystem and support subsystem contribute in improving the product.

Example 2

The term ($S_4S_5L_{132}$) of the fourth group in the characteristic polynomial represents the development of a new product through customer feedback, surveys and benchmarking with competitor firms. Information about new product is provided by support subsystem (surveys and customer feedback) and output subsystem (competitor benchmarking). This information serves as inputs for the manufacturing subsystem and a new product is developed. Other aspects such as feasibility of production, production schedules, number of products to be produced etc. are then decided upon by the management subsystem.

Similarly, physical significance of various other terms of the permanent multinomial can be derived and with this approach, the total structural analysis can be carried out by taking into consideration all the possible structural tests which are 22 in number for the agile manufacturing system under consideration based on the terms of the characteristic multinomial.

3.4 Identification of agile manufacturing system structure

For the agile manufacturing system under consideration, 22 terms of the permanent multinomial are obtained which identify all possible structural patterns contributing towards varying goals of the agile manufacturing system and also serve as 22 structural tests that may be used to analyze the agile manufacturing system in 22 distinct ways. So, a systematic technique for the structural identification and comparison of the agile manufacturing systems has been developed.

There are six groups of structural members of the agile manufacturing system. The characteristic features of all these six groups as identified in equation (3.8) are summarized as below:

(1) The first group consists of a single term representing a set of five subsystems singularly representing each subsystem. The identification set is $S_1/S_2/S_3/S_4/S_5$.

(2) The second group terms should have four singular subsystems and a subsystem dependent on itself. Such condition is non-existent in the agile manufacturing system and thus the second group is found to be absent.

(3) The third group has four terms, each term a set of three singular subsystems and a “two subsystem loop” or a dyad. The identification set may be written as $S_i/S_j/S_k/S_{lm}$.

(4) The fourth group has six terms consisting of a set of two singular subsystems and a three subsystem loop. The identification set is $S_i/S_j/S_{klm}$.

(5) The fifth group consists of two subgroups having two and seven terms, each having one singular subsystem and the first subgroup has two “two subsystem dyads and the second subgroup has a set of one ‘four subsystem loop.’” The corresponding identification sets are $S_i/S_{jk}/S_{lm}$ and S_i/S_{jklm}, respectively.

(6) Similarly, the sixth group has two terms, each having a set of five subsystem loop.

Similarly, the identification sets may be written as and S_{ijklm}.

So, from the terms of the permanent or the characteristic multinomial, the identification set for any manufacturing system may be written as:

$$/J_1/J_2/J_3/J_4/J_{51}/J_{52}/J_6/ \tag{3.9}$$

where J_k represent the total number of terms in the k^{th} grouping and J_{kl} represent the total number of terms in the l^{th} sub-grouping of the k^{th} group.

3.5 Comparison of the agile manufacturing system structure

Comparison of the agile manufacturing system structure is very important in today’s highly competitive environment. The competitiveness of a manufacturer depends upon the availability of resources as well as upon the practices used in various components of the agile manufacturing system and most importantly the interactions. All these attributes are represented in the manufacturing system structure. Thus, the terms of the permanent function, which represent real subsets of the manufacturing system, can be used to compare different alternative choices for the manufacturing system structure. This structure-based comparison will also aid in the process of developing new design of agile manufacturing system, business processes restructuring and for benchmarking, which have become essential in the modern era. The coefficient of similarity and dissimilarity give a systematic method of comparison of the agile manufacturing system structure.

If the number of distinct terms in the l^{th} sub-grouping of the k^{th} grouping of the permanent function of the two manufacturing systems under consideration be denoted by J_{kl} and J'_{kl}, respectively, the coefficient of dissimilarity and similarity may be defined by two criteria namely criterion 1 and 2 as given below.

Criterion 1. If the difference of the number of terms of the j^{th} subgroup of and i^{th} group of the permanent multinomial, $\Phi_{kl} = [J_{kl} - J'_{kl}]$.

Then;

$$\text{The coefficient of dissimilarity, } C_{d\text{-}1} = \frac{1}{Y_1} \sum_k \sum_l \Phi_{kl} \quad (10)$$

$$\text{where; } Y_1 = \text{maximum } [\textstyle\sum_k \sum_l J_{kl} \text{ and } \sum_k \sum_l J'_{kl}].$$

Though the criterion 1 developed above presents a relatively simple method of quantifying the structural difference between the agile manufacturing systems but this may cause loss of comparison information in the coefficient of dissimilarity. This is because of the fact that the value of Φ_{kl} may be negative depending upon the structural difference in the manufacturing systems under consideration. As a result, the subtraction operations may be involved and may cause limitation in the coefficient of similarity.

So, a better criterion by using the squares of the comparison values, Φ_{kl} is developed in equation (3.11).

Criterion 2. The coefficient of dissimilarity by this criterion is given as:

$$C_{d\text{-}2} = \left[\frac{1}{Y_2} \sum_k \sum_l \Phi_{kl}^2\right]^{1/2} \qquad (11)$$

$$\text{Where } Y_2 = \text{maximum } \left[\textstyle\sum_k \sum_l (J_{kl})^2 \text{ and } \sum_k \sum_l (J'_{kl})^2\right]$$

$$\text{And } \Phi_{kl} = [J_{kl} - J'_{kl}].$$

It can be seen from the structure of the equation, the value for the coefficient of dissimilarity will lie between 0 and 1, the coefficient of similarity can be calculated as:

$$C_{s\text{-}1} = 1 - C_{d\text{-}1} \qquad (12)$$

$$C_{s\text{-}2} = 1 - C_{d\text{-}2} \qquad (13)$$

Where $C_{s\text{-}1}$ and $C_{s\text{-}2}$ are the coefficients of similarity of two different agile manufacturing systems under consideration by criteria 1 and 2, respectively.

The value of one, for the coefficient of similarity indicates that the two manufacturing system structures are completely similar. Structural similarity or dissimilarity may be indirectly, a measure of the performance's similarity/dissimilarity as the terms of the permanent multinomial represent real subsets of the agile manufacturing system contributing towards different goals. So, differences or similarities in these terms indicate variation in the agile manufacturing system's capacity in contributing towards these varied goals. The total comparison may be carried out based on the characteristic values for different subsystems. Since all the characteristic values and interaction levels are incorporated in the permanent function of the agile manufacturing system, the numerical values as assigned by experts to all these terms will result in single composite numerical score of the total agile manufacturing system. This also forms a basis for classifying agile manufacturing systems based on their structure by comparing it with a benchmarked agile manufacturing system.

3.6 Procedure to develop graph theoretic agile manufacturing system structural model

The proposed graph theoretic model can be implemented by any organisation by following the step by step procedure mentioned below. This would help the manufacturers in understanding the system comprehensively and would also be helpful in taking improvement decisions as and when required. The procedure is as follows:

1. Develop a business strategy of the organisation i.e. vision, mission and goals.
2. Identify the attributes of the agile manufacturing system.
3. Identify various subsystems.
4. Develop a hierarchical tree structure for the agile manufacturing system showing all the subsystems and their components.
5. Develop a block diagram indicating various interactions between the subsystems.
6. Develop graph theoretic models of the total system.
7. Develop agile manufacturing system permanent matrix.
8. Develop permanent multinomial.
9. Perform structural analysis by considering various terms of the permanent multinomial and their physical representations.
10. Evaluate alternate structural design by manipulation of the terms in the permanent multinomial.

Decision makers can use agile manufacturing system tree, integration block diagram, variable permanent function and its physical representations for in-depth understanding for taking decisions and creating short term and long term manufacturing strategies for different types of products, markets and customers.

3.6.1 Example of structural comparison

In order to illustrate the methodology for total structural analysis let us consider the agile manufacturing system having graph as shown in figure 3.3. Let us call this agile manufacturing system A. Now let us consider another agile manufacturing system B having characteristics similar to agile manufacturing system A except for one difference that there is no link between the management subsystem and the input subsystem.

Now, following the steps given in the procedure, the permanent multinomial can be derived for agile manufacturing system B. The structural comparison between the two agile manufacturing systems is given below.

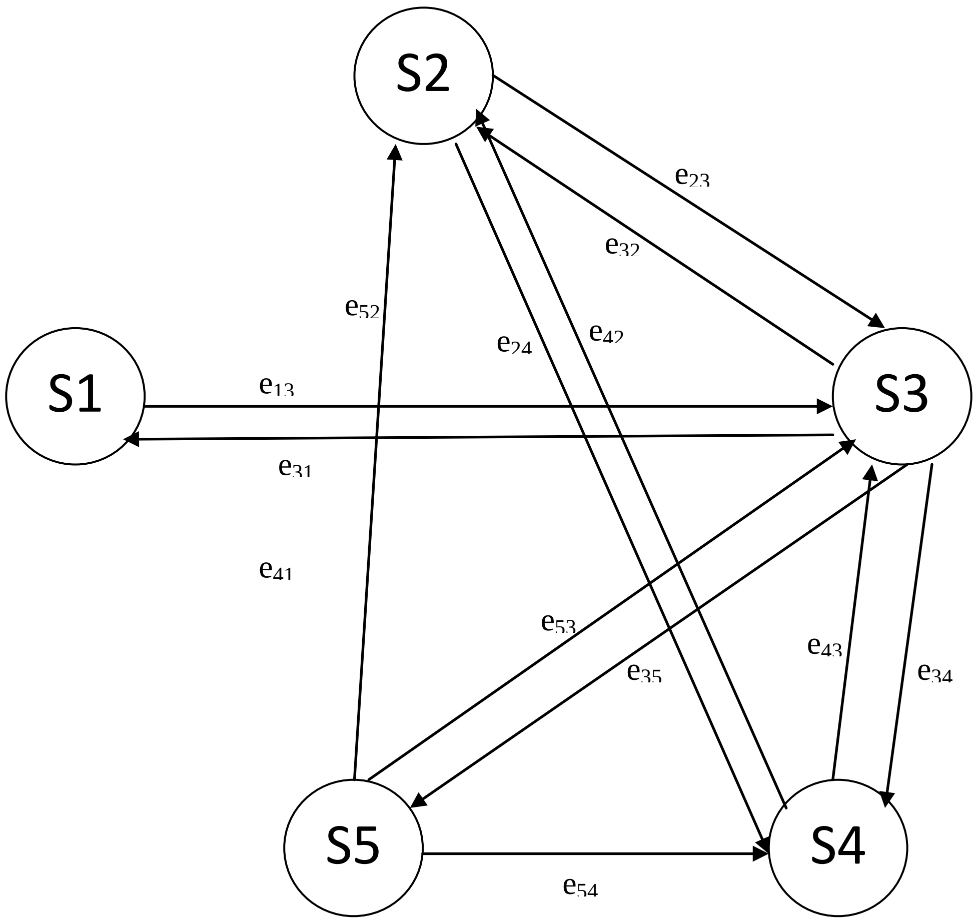

Figure 3.5 Structural graph of agile manufacturing system with missing feedback link from management subsystem to input subsystem

As seen from the figure, the feedback link from the management subsystem to the input subsystem in the agile manufacturing system B is missing.

By graph theoretic methodology, the identification sets for both the agile manufacturing systems A and B are written as:

$/J_1/J_2/J_3/J_4/J_{51}/J_{52}/J_6/ = 1/0/4/6/2/7/1/$ and

$/J_1/J_2/J_3/J_4/J_{51}/J_{52}/J_6/ = 1/0/5/4/1/4/1/$ respectively.

Now, by making use of coefficients of similarity and dissimilarity, the change in structure of the two agile manufacturing systems can be quantified, making use of criteria 1 and 2 as shown below;

$$C_{d-1} = 0.444 \quad C_{s-1} = 0.556$$

$$C_{d-2} = 0.434 \quad C_{s-2} = 0.566$$

Both criteria give almost same values because of the fact that value of Φ_{kl} remains positive. Here, criteria 1 can give us an accurate value but if some terms are missing from the first agile manufacturing system and present in the second, resulting in a negative value of Φ_{kl}, then criteria 2 would be helpful in calculating the values.

CHAPTER 4
EVALUATION, COMPARISON, RANKING AND SELECTION OF OPTIMUM AGILE MANUFACTURING SYSTEM

4.1 Introduction

Agile manufacturing systems are rapidly increasing in number due to ever changing customer demands, shorter product life cycles, higher product variety, economy of production and highly competitive global market. The purpose of this research is to develop and maintain reliable and exhaustive database of agile manufacturing systems based on their different pertinent attributes. This database can be used to standardize the agile manufacturing system mode according to the required pertinent attributes when the product information is available to a manufacturer. This is in turn helps in reducing lead time to market. The selection procedure allows quick short-listing from a very large number of agile manufacturing system modes to a list of potentially suitable agile manufacturing system modes by using elimination search based on the required pertinent attributes. Then the alternative agile manufacturing systems are ranked by employing attribute based specification methods. The ranks are calculated with respect to the best possible agile manufacturing system for a particular product. This is a novel attempt to create a database by identifying maximum possible number of attributes for agile manufacturing systems. This helps in attribute based evaluation, comparison, ranking and selection.

With the product life cycles becoming shorter and shorter, there has been an increase in the number of agile manufacturing system modes which have different capabilities. The selection of an agile manufacturing system mode depends upon various considerations such as re-configurability, re-usability, scalability, internal (i.e. dynamic market changes and technological changes) and external (i.e. resource shortage and machinery breakdowns) turbulence and many more. This problem seems to be more complex when one realises that there are over 50 attributes which need to be considered before a particular mode is selected.

From the literature review in chapter 2, it can be said that no one has used the TOPSIS technique in the field of agile manufacturing systems and most of the literature on agile manufacturing systems deals with strategies, technologies, people and systems.

4.2 Agile Manufacturing Attributes

It is very important to identify the agile manufacturing system attributes carefully so that a proper comparison can be made between the alternatives. The characteristics of the product to be manufactured will depend upon the choice of agile manufacturing system; therefore, it is very important to properly identify the attributes.

4.2.1 Quantification and measurement of attributes

The agile manufacturing system has both quantitative and qualitative attributes. The problem arises when qualitative attributes are pertinent in nature. This problem can be solved by rating these attributes on a scale of 1 – 5, with 1 being the lowest and 5 being the highest. The rating can be done by a group of experts with each person specializing in at least one of the field of agile manufacturing. A similar approach has to be used for the informative attributes which just give information about some attribute of the agile manufacturing system such as capacity of a machine, which will be denoted by some number whose numerical value will have no significance. They cannot be used for the mathematical treatment since they are just a representation and numeric value has no significance.

4.3 Identification of attributes and coding scheme

The attributes are divided into 9 broad categories as strategy parameters, system parameters, technology parameters, input parameters, management parameters, support parameters, manufacturing process parameters, output parameters and people. They are given as follows:

Strategy parameters

1. Re-configurability
2. Re-usability
3. Scalability
4. Virtual enterprise
5. Control Strategies
6. Core competencies
7. Re-engineering
8. Supply chain integration
9. Responsive logistics
10. Heterogeneous computer systems
11. Concurrent engineering

12. STEP (Standard for the Exchange of Product model data)

System parameters

13. MRP II
14. Internet
15. Supplier integrated information systems
16. CAD/CAE
17. ERP
18. Multi–agent system
19. TQM
20. CIM
21. ABC
22. JIT
23. CAPP

Technology parameters

24. Rapid prototyping tools
25. Robots
26. Electronic data interchange
27. Modular assembly software
28. Real – time control
29. Information technology
30. Holonic manufacturing system

Input parameters

31. Agile material
32. Agile capital
33. Agile capacity planning
34. Agile design engineering
35. Agile production scheduling
36. Agile Suppliers

Management parameters

37. Agile Performance monitoring
38. Agile planning & control
39. Agile quality management

Support parameters

40. Agile information processing
41. Maintenance engineering
42. DDIS (Dynamic data interchange scheme)
43. Finance

Manufacturing process parameters

44. Maximum operational flexibility
45. Agile machinery utilization
46. Agile material handling system
47. Layout flexibility
48. Safety & facility to workers

Output parameters

49. Agile sales & distribution
50. Agile waste disposal
51. Brand image

People parameters

52. Flexible work force
53. Knowledge workers
54. Skills in IT
55. Empowered workers
56. Multi-lingual
57. Top management support.

The above mentioned attributes can be coded and tabulated as:

Parameters/Code												
Strategy	1	2	3	4	5	6	7	8	9	10	11	12
System	13	14	15	16	17	18	19	20	21	22	23	
Technology	24	25	26	27	28	29	30					
Input	31	32	33	34	35	36						
Management	37	38	39									
Support	40	41	42	43								
Manufacturing process	44	45	46	47	48							
Output	49	50	51									
People	52	53	54	55	56	57						

Table 4.1 Agile manufacturing system attribute coding scheme.

4.4 Illustration of coding

In order to understand the proposed coding scheme let us consider an attribute. Suppose that coding has to be done for agile machinery utilization. This is explained below:

Machine Utilization (hours)	Code
Unspecified	0
0-8	1
8–10	2
10–12	3
12–16	4

16–20	5
20–24	6

Table 4.2 Coding scheme for agile machinery utilization

This code will be used to specify the agile machinery utilization in the respective shell number 45.

As mentioned earlier, the literature on agile manufacturing systems consists of the attributes above. These have been depicted in the table below.

Sr. No.	Attribute	Information	Code
1	Re-configurability	Available	1
2	Re-usability	Available	1
3	Scalability	Available	1
4	Virtual enterprise	Available	1
5	Control strategies	Available	1
6	Core competencies	Unavailable	0
7	Re-engineering	Available	1
8	Supply chain integration	Available	1
9	Responsive logistics	Available	1
10	Heterogeneous computer systems	Available	1
11	Concurrent engineering	Available	1
12	STEP	Unavailable	0
13	MRP II	Available	1
14	Internet	Unavailable	0

Sr. No.	Attribute	Information	Code
15	Supplier integrated information systems	Available	1
16	CAD/CAE	Available	1
17	ERP	Available	1
18	Multi–agent system	Available	1
19	TQM	Available	1
20	CIM	Available	1
21	ABC	Unavailable	0
22	JIT	Available	1
23	CAPP	Available	1
24	Rapid prototyping tools	Available	1
25	Robots	Available	1
26	Electronic data interchange	Available	1
27	Modular assembly software	Available	1
28	Real – time control	Available	1
29	Information technology	Available	1
30	Holonic manufacturing system	Available	1
31	Agile material	Unavailable	0
32	Agile capital	Available	1
33	Agile capacity planning	Available	1
34	Agile design engineering	Available	1
35	Agile production scheduling	Available	1

Sr. No.	Attribute	Information	Code
36	Agile Suppliers	Available	1
37	Agile Performance monitoring	Available	1
38	Agile planning & control	Available	1
39	Agile quality management	Available	1
40	Agile information processing	Available	1
41	Maintenance engineering	Unavailable	0
42	DDIS	Available	1
43	Finance	Unavailable	0
44	Maximum operational flexibility	Available	1
45	Agile machinery utilization	Available	1
46	Agile material handling system	Available	1
47	Layout flexibility	Available	1
48	Safety & facility to workers	Available	1
49	Agile sales & distribution	Available	1
50	Agile waste disposal	Unavailable	0
51	Brand image	Unavailable	0
52	Flexible work force	Available	1
53	Knowledge workers	Available	1
54	Skills in IT	Available	1
55	Empowered workers	Available	1
56	Team-based work	Available	1

Sr. No.	Attribute	Information	Code
57	Top management support	Available	1

Table 4.3 Agile manufacturing system attributes information.

The table shows that few of the attributes have been coded as 0 i.e. no information about them is available. This information if provided can help in making the database exhaustive.

The information from table 4.3 can be used to create agile manufacturing system code as shown below.

Parameters/Code												
Strategy	1	1	1	1	1	0	1	1	1	1	1	0
System	1	0	1	1	1	1	1	1	0	1	1	
Technology	1	1	1	1	1	1	1					
Input	0	1	1	1	1	1						
Management	1	1	1									
Support	1	0	1	0								
Manufacturing process	1	1	1	1	1							
Output	1	0	0									
People	1	1	1	1	1	1						

Table 4.4 Agile manufacturing system code

4.5 The 3-stage selection procedure

4.5.1 Elimination Search

Of all the attributes that have been identified, not all would be important while selecting an agile manufacturing system for a particular product/user. There will be a few of the attributes which are important, known as pertinent attributes. The values for these attributes are assigned by experts in the field. Now, only these "pertinent attributes" will be the main focus of the selection procedure. Based on the values of these attributes, a shortlist of agile manufacturing systems can be obtained from the database. This can be achieved by scanning the database for pertinent attributes, one at a time.

4.5.2 Evaluation procedure

A database is formed which comprises of all the solutions after considering all the pertinent attributes. The problem is then reduced to finding the optimum solution out of these satisfying solutions. To achieve this, the solutions are ranked in order of merit by the selection procedure.

The first step is to represent all the information about the satisfying solutions in a matrix known as decision matrix. Each row in this matrix represents one mode of the agile manufacturing system and each column represents an attribute related to that mode. So, an element d_{ij} of the decision matrix D corresponds to the j^{th} attribute for the i^{th} agile manufacturing system mode. Consequently, if the number of shortlisted agile manufacturing system modes is "*m*" and the number of pertinent attributes is "*n*", the decision matrix would be a *m* x *n* matrix.

4.5.3 Normalized specifications

The decision matrix D, developed in the previous step is used to construct a normalized specification matrix N. This normalized matrix is developed to bring the data within a particular range or scale besides providing dimensionless magnitudes. The normalized specification matrix contains the magnitudes of all the attributes of the agile manufacturing modes on a common scale of 0 to 1. Basically, each attribute is compared to all the other attributes to develop this matrix. Any element of the normalized matrix can be calculated as

$$n_{ij} = d_{ij}/(\sum_{i=1}^{n} d_{ij}^2)^{1/2} \qquad (4.1)$$

where d_{ij} is an element of the decision matrix D.

Now information is obtained from a manufacturer or a group of experts on the relative importance of one attribute with respect to another. This information is in terms of a ratio and all these pair wise comparisons are stored in matrix known as relative importance matrix, A which is *n* x *n* matrix. Any element a_{ij} of the matrix will contain the relative importance of the i^{th} attribute over the j^{th} attribute. The symmetric terms of this matrix will be reciprocals of each other and the diagonal elements will be unity.

The information stored in matrix A is modified into a representation that gives the relative weights of all attributes taken together such that the cumulative sum of the weights is equal to 1. In order to find the weights, the eigen vector method is used. The weights associated with matrix A are calculated as;

$$Ax = \lambda x \qquad (4.2)$$

Where λ is the eigen value of A and x is the corresponding eigen vector. For *n* x *n*A, there are *n* eigen values λ_i, for $i = 1,2,.....,n$ and corresponding to λ_i, there are n eigen vectors x_i, for $i = 1,2,....,n$. Vector w is now found in the following manner:

1. Take eigen vector, x_{max} corresponding to the largest eigen value λ_{max}, as all elements of x_{max} are either positive or negative.

2. Find the sum of the elements of x_{max} as

$$\alpha = \sum_{i=1}^{n} (x_i)_{max} \qquad (4.3)$$

3. Find weight vector as

$$w = (x_{max})/\alpha \text{ such that } \sum_{i=1}^{n} w_i = 1 \qquad (4.4)$$

4.5.4 Weighted normalized specification

The attributes can be classified as cost attributes and benefit attributes. As the name suggests, cost attributes are the ones which serve as inputs to the pricing of the product. These might not change much over time. On the other hand, benefit attributes are the ones which are more consumer-centric. These attributes provide information about the benefits of the product/brand such as product characteristics and service characteristics.

The weights thus obtained from the relative importance matrix have to be applied to the normalized specifications as all the attributes have different importance while selecting the agile manufacturing mode for a particular application. This is achieved by combining the relative weights and normalized specifications in a matrix known as weighted normalized matrix, V. This matrix will give the true comparable values of the attributes. This is obtained as follows:

$$V = \begin{bmatrix} w_1 n_{1,1} & w_2 n_{1,2} & \cdots & w_n n_{1,n} \\ w_1 n_{2,1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ w_1 n_{m,1} & w_2 n_{m,2} & \cdots & w_n n_{m,n} \end{bmatrix} = \begin{bmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,n} \\ v_{2,1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ v_{m,1} & v_{m,2} & \cdots & v_{m,n} \end{bmatrix} \quad (4.5)$$

4.6 Ranking and selection procedure

4.6.1 TOPSIS method

The ranking of the agile manufacturing system modes can be done by mathematically (TOPSIS method) as follows:

The weighted normalized matrix V is used to obtain +ve and –ve benchmark modes (v^+ and v^- respectively), where both the benchmark modes are hypothetical, which are supposed to have the best and worst possible attribute magnitudes. The TOPSIS method is based on the concept that the optimum (chosen) option should have the shortest distance from the +ve benchmark mode (best possible mode, v^+) and farthest from the –ve benchmark mode (worst possible mode, v^-).

The separation measures from the +ve and –ve benchmark modes are calculated as S_i^* and S_i^- respectively as:

$$S_i^* = \left(\left[\sum_{j=1}^{n}(v_{ij} - v_j^+)^2\right]\right)^{1/2} \quad (i = 1,2,....,m) \qquad (4.6)$$

$$S_i^- = \left(\left[\sum_{j=1}^{n}(v_{ij} - v_j^-)^2\right]\right)^{1/2} \quad (i = 1,2,....m) \qquad (4.7)$$

Now, the relative closeness to the +ve benchmark agile manufacturing mode is calculated. This relative closeness is defined as the measure of the suitability of the mode for the chosen product/application on the basis of the attributes considered. The mode with the largest C* is preffered.

$$C^* = S_i^- / (S_i^+ + S_i^-) \qquad (4.8)$$

Ranking of the modes with decreasing value of C* indicates the most preferred and the least preferred solutions.

4.6.2 Illustrative example

Suppose that an agile manufacturing mode has to be selected for a T.V. manufacturer for which the minimum requirements are given as follows:

1	Number of units (per day)	12000
2	Lot Size	4000
3	Material handling	Semi–automatic
4	Human intervention	Moderate (preferable)
5	Variety of products (variants)	5
6	Defects	Minimum

According to the requirements, the possible solutions can be generated from the database by elimination search. These are tabulated in table 4.

System	**No. of units**	**Lot size**	**Material handling**	**Human intervention**	**Variety**
A	14000	3500	Automatic	Moderate	8
B	13000	3000	Semi–automatic	Maximum	6
C	15000	4000	Automatic	Minimum	5
D	16000	4500	Automatic	Moderate	7
E	18000	4000	Automatic	Minimum	9

Table 4.4. Attributes for the short listed agile manufacturing modes

The selection procedure is as follows:

Step 1. Formation of decision matrix, D. The rows of matrix are the manufacturing modes and the columns represent their attribute values. Here, some of the attributes are qualitative in nature (material handling and human intervention). These will be ranked on a scale of 1 – 5 as explained in section 2.1

$$D = \begin{bmatrix} 14000 & 3500 & 5 & 3 & 8 \\ 13000 & 3000 & 2 & 5 & 6 \\ 15000 & 4000 & 5 & 1 & 5 \\ 16000 & 4500 & 5 & 3 & 7 \\ 18000 & 4000 & 5 & 1 & 9 \end{bmatrix} \qquad (4.9)$$

Step 2. In this step, relative importance matrix A is developed. A group of experts will determine the relative importance of the attributes with respect to each other and the symmetric terms will be reciprocals of each other.

$$A = \begin{bmatrix} 1 & 1 & 2 & 0.5 & 0.33 \\ 1 & 1 & 0.5 & 2 & 2 \\ 0.5 & 2 & 1 & 3 & 2 \\ 2 & 0.5 & 0.33 & 1 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & 1 \end{bmatrix} \qquad (4.10)$$

Step 3. In this step, the maximum eigen value from the relative importance matrix A is found out.

$$(A - \lambda_{maxI}) = \begin{bmatrix} 1-\lambda & 1 & 2 & 0.5 & 0.33 \\ 1 & 1-\lambda & 0.5 & 2 & 2 \\ 0.5 & 2 & 1-\lambda & 3 & 2 \\ 2 & 0.5 & 0.33 & 1-\lambda & 0.33 \\ 3 & 0.5 & 0.5 & 3 & 1-\lambda \end{bmatrix} \qquad (4.11)$$

$$(A - \lambda_{maxI}) = 0$$

$$\lambda = 6, -0.2095 + 2.2910i, -0.2095 - 2.2910i, -.02762 + 0.4806i, -.02762 - 0.4806i$$

$$\lambda_{max} = 6$$

$$(A - \lambda_{maxI}) = \begin{bmatrix} -5 & 1 & 2 & 0.5 & 0.33 \\ 1 & -5 & 0.5 & 2 & 2 \\ 0.5 & 2 & -5 & 3 & 2 \\ 2 & 0.5 & 0.33 & -5 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & -5 \end{bmatrix} \quad (4.12)$$

Step 4. Now weights for each attribute are calculated using the eigen vector associated with maximum eigen value.

$$(A - \lambda_{maxI})w = 0 \quad (4.13)$$

$$\begin{bmatrix} -5 & 1 & 2 & 0.5 & 0.33 \\ 1 & -5 & 0.5 & 2 & 2 \\ 0.5 & 2 & -5 & 3 & 2 \\ 2 & 0.5 & 0.33 & -5 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & -5 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \end{bmatrix} = 0 \quad (4.14)$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = 0 \quad (4.15)$$

$w_1 = 0.1761$

$w_2 = 0.2042$

$w_3 = 0.2668$

$w_4 = 0.243$

$w_5 = 0.2286$

Step 5. Now the normalized specification matrix is calculated which helps in providing dimensionless elements of the matrix.

$$r_{ij} = d_{ij}/(\textstyle\sum_{i=1}^{m} d_{ij}^2)^{1/2} \quad (4.16)$$

$$N = \begin{bmatrix} 0.9702 & 0.1087 & 0.6355 & 0.1217 & 0.3559 \\ 0.1029 & 0.29 & 0.2542 & 0.7304 & 0.3741 \\ 0.1102 & 0.435 & 0.4321 & 0.3652 & 0.6023 \\ 0.1632 & 0.2175 & 0.2504 & 0.4869 & 0.3468 \\ 0.0404 & 0.4263 & 0.1398 & 0.1217 & 0.3285 \end{bmatrix} \quad (4.17)$$

Step 6. Now the relative importance of the attributes is incorporated with their normalized values to create a unique agile manufacturing mode.

$$V = \begin{bmatrix} 0.1709 & 0.0222 & 0.1696 & 0.0151 & 0.0814 \\ 0.0181 & 0.0592 & 0.0678 & 0.0908 & 0.0855 \\ 0.0194 & 0.0888 & 0.1153 & 0.0454 & 0.1355 \\ 0.0287 & 0.0444 & 0.0668 & 0.0605 & 0.0793 \\ 0.0071 & 0.087 & 0.0373 & 0.0151 & 0.0751 \end{bmatrix} \quad (4.18)$$

The above matrix is an all-inclusive matrix which takes care of the attribute values and their relative importance. Thus, it will provide good basis for comparison, with each other and the benchmark agile manufacturing mode.

4.7 Usefulness of the proposed methodology to the manufacturer

1. The pertinent attributes can be controlled by the manufacturer in order to suit the requirements of the user/product precisely.
2. The magnitude of the attributes reflects the market trends. This in turn can be used for future modifications in the product.
3. The database can be used to produce maximum number of products in minimum possible time economically.
4. The generated hypothetically best agile manufacturing system is useful for industries in setting up the benchmark agile manufacturing system.

4.8 Step-by-step procedure for the industry

1. Decide about the short term and long term strategy to develop a series of agile manufacturing system modes.
2. Carry out cause and effect analysis to identify all the relevant attributes and prepare a list of attributes.
3. Carry out SWOT analysis to decide the attribute based specification.
4. Using Morphological chart procedure to identify different design solutions (alternatives).
5. Carry out Elimination search based on pertinent attributes to reduce long list into manageable list of alternatives satisfying all the requirements.
6. Attribute based evaluation using TOPSIS is carried out for all the feasible solutions using MADM-TOPSIS approach.
7. Rank all these feasible solutions in order of preference based on the procedure proposed.

CHAPTER 5
CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

The work presented in this thesis is focussed on modeling, evaluation, optimum selection and analysis of agile manufacturing system using system approach. Two different methodologies are presented to achieve the objectives of this work. Graph Theoretic Approach is presented in Chapter 3 in order to achieve the objective of developing the systems model for the structural analysis of agile manufacturing system. This model integrates the different constituents of the agile manufacturing system and describes the whole system. The contribution of the work regarding Graph Theoretic Approach can be summarized as:

1. This methodology builds a flexible and comprehensive model, which has the capability to consider the interactions between various components of the total agile manufacturing system.
2. The present work identifies five subsystems, which parameterize the agile manufacturing system. Also interactions between the components are identified under four different categories.
3. The systems methodology consists of the agile manufacturing system structure graph, the agile manufacturing system matrix, and agile manufacturing system permanent function. The system graph is the mathematical representation of the structural characteristics and their interactions, useful for visual modeling and analysis. The agile manufacturing system matrix converts graph into another mathematical form. This matrix representation is powerful tool for storage and retrieval of agile manufacturing systems in computer database.
4. The agile manufacturing system permanent function is a mathematical model characterizing the structure of the agile manufacturing system and also helps one to determine the agile manufacturing system numerical index. This numerical index is used for comparison, ranking, and optimum selection.
5. The model may serve as a framework for developing various quantitative performance indices in various dimensions of performance, viz. reliability, flexibility, quality, etc. giving an agile manufacturing system measure of the overall performance of the agile manufacturing system.

Multi-Attribute Decision Making (MADM) approach is presented in Chapter 4 in order to achieve the objective of evaluation and optimum selection of agile manufacturing system from different alternatives. It identifies the various attributes needing to be considered for the optimum evaluation and selection of agile manufacturing systems. It also provides an n-digit coding scheme for agile manufacturing system modes depicting the various attributes. It recognizes the need for and processes the information about relative importance of attributes for a given application without which inter-attribute comparison is not possible. It presents the result of the information processing in terms of a suitability index, which is used to rank the agile manufacturing system mode in the order of their suitability for the given application. The contribution of the work regarding MADM approach can be summarized as

1. The proposed method provides a coding scheme, which is a collection of 57 attributes for characterization of agile manufacturing system and is useful in defining the agile manufacturing system accurately and precisely. The coding scheme is illustrated with the help of an example.
2. A 3-stage selection procedure including elimination search, TOPSIS approach on the basis of identified pertinent attributes and the separation of each alternative from generated hypothetically best and worst agile manufacturing systems, helps in ranking of all the agile manufacturing system alternatives.
3. The proposed methodology ensures that the selected agile manufacturing system is nearest to the hypothetical best agile manufacturing system and farthest from the hypothetical worst agile manufacturing system.
4. The developed methodology permits the consideration of both types of attributes such as larger-the-better and smaller-the-better together and provides the ranking accordingly.
5. Evaluation and ranking of an agile manufacturing system based on the mathematical and graphical approaches along with the illustrative examples are presented.
6. It is recommended that the information about all the attributes related to an agile manufacturing system should be maintained as knowledge base for future usage by the manufacturer. This information will be helpful to the agile manufacturing system designer, maintenance personnel, user, etc.

5.2 Future Scope

1. A computer program will be developed to carry out all the calculations in both the methodologies.
2. A computer based electronic database for the storage and retrieval of different attributes of the agile manufacturing system will be developed. This will make the selection procedure easy.
3. Cause and effect analysis and sensitivity analysis will be done to improve the quality and reliability of the agile manufacturing system.
4. An attempt will be made to develop various quantitative performance indices in various dimensions of performance such as reliability, efficiency, quality, etc.
5. Graph Theoretic Approach will be developed to analyze the agile manufacturing system by obtaining the permanent functions at the system as well as subsystem levels.

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