STUDY OF SOME SELECTED ISSUES IN THE DESIGN AND DEVELOPMENT OF FLEXIBLE MANUFACTURING SYSTEM

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CANDIDATE'S DECLARATION

I, hereby, declare that this thesis entitled **STUDY OF SOME SELECTED ISSUES IN THE DESIGN AND DEVELOPMENT OF FLEXIBLE MANUFACTURING SYSTEM** by **SUMAN**, being submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in MECHANICAL ENGINEERING under Faculty of Engineering & Technology of YMCA University of Science & Technology Faridabad, during the academic year 2017-2018, is a bonafide record of my original work carried out under guidance and supervision of **Dr. TILAK RAJ, PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING** and has not been presented elsewhere.

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I further declare that to the best of my knowledge, the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

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ABSTRACT

Competitiveness in market and modern lifestyle trends have put up marvelous challenges to manufacturing industries. A high degree of flexibility is required to upgrade the technology, quick delivery to market and respond rapidly to the changing demands of the customers. To meet these challenges forced by today’s dynamic market conditions, the manufacturing companies need to adopt advance manufacturing systems. FMS has been viewed as ideal solution for these challenges and in gaining competitive advantage.

An extensive literature review has been conducted regarding different issues affecting the design and development of an FMS to understand their importance and impact in an FMS. A number of factors/measures affecting flexibility, performance, material handling system (MHS) such as automated guided vehicles (AGVs) and fixture and pallets have been indentified and analyzed through a questionnaire-based survey among the Indian manufacturing industries and interactions with the experts both from the industry and academia.

Weighted Interpretive structural modeling (W-ISM) and Interpretive structural modeling (ISM) techniques has been utilized to indentify the mutual interaction and interpretation of factors in terms of their driving and dependence powers. A method of effectiveness index (EI) and MICMAC analysis have been used to identify the key factors. The evaluation of the most appropriate performance measures in the manufacturing sector is one of the strategic issues that affect the FMS performance. With this aim, an effort has been made in the current research work to analyze the impact of different performance measures of FMS through Graph theoretic approach (GTA), Simple additive weighting (SAW) and Weighted product method (WPM) methodologies. 0-1 Linear integer programming has been utilized to find out the optimized path layout for individual loaded AGV. A general linear optimization computer software package, named LINGO 14 is used to find out the optimal flow path for the layout. Various aspects related to flexible fixture and pallet have been studied and discussed in the present work. A case study has been discussed and a design of pneumatically controlled flexible fixture with pallet has been proposed for handling a variety of workpart configurations on drilling heads. Analytic hierarchy process (AHP) and Analytic network process (ANP) have been utilized to find out the best manufacturing system. At last, some alternate technologies other than CNC in the design and development of FMS has been studied and discussed in this research.

The major contributions of this research are as given below:

- The present research provides a comprehensive review of the literature and identifies contemporary issues related to design and development of FMS.
- The inclination of Indian manufacturing industries towards different issues and factors related to FMS has been found out.
- Various measures related to machine, product and routing flexibilities are identified and their drive and dependence power have been analyzed to identify the most significant key factors affecting different flexibilities.
- Various issues related to AGVs have been analyzed. Design and development of AGV’s is affected by various factors, these factors are identified and analyzed. Shortest possible path has been determined for a particular case for fulfilling the requirements of different machines in FMS.
- Various factors affecting the performance of the FMS have been identified and analyzed.
- Index of performance (IOP) has been evaluated to quantify the various performance measures related to FMS and prioritization of different performance measures has been done. The performance index of any manufacturing industry can be determined with the help of this IOP.
- Prioritization of different performance measures has been done with help of GTA, SAW and WPM approaches.
- Various aspects related to flexible fixture and pallets have been analyzed. A case study has been discussed and a design of pneumatically controlled flexible fixture and pallet has been proposed to handle a variety of workpart configurations on drilling heads.
- A comparative study of various factors in different manufacturing systems has been done and among all these manufacturing systems, the best manufacturing system has been found out with the help of AHP and ANP techniques.
- At last, some alternate technologies other than CNC in design and development of FMS have been studied.

Keywords: FMS; key variables; EI; performance; flexibility; factors; variables; Performance measures; ISM; W-ISM; GTA; AHP; ANP; SAW; WPM; 0-1 Linear Integer Programming; Optimization; Flow Path Layout; Lingo 14; CAFD; FF; AGV; MHS; HFMS; CIM; CNC; DSP; open-architecture CNC; THINC.

TABLE OF CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Sr. No.	Description	Abbreviations
1.	Flexible Manufacturing System	FMS
2.	Computer Numerical Control	CNC
3.	Material Handling System	MHS
4.	Flexible Manufacturing Cell	FMC
5.	Numerical Control	NC
6.	Automated Guided Vehicle	AGV
7.	Weighted Interpretive Structural Modeling	W-ISM
8.	Graph Theoretic Approach	GTA
9.	Simple Additive Weighting	SAW
10.	Weighted Product Method	WPM
11.	Analytic Network Process	ANP
12.	Analytic Hierarchy Process	AHP
13.	Interpretive Structural Modeling	ISM
14.	Effectiveness Index	EI
15.	Concept of Collaborative Planning, Forecast and Replenishment	CPFR
16.	Computer Aided Fixture Design	CAFD
17.	Multi-Criteria Decision Making	MCDM
18.	Humanized Flexible Manufacturing System	HFMS
19.	Computer Integrated Manufacturing	CIM
20.	Single Machine Cell	SMC
21.	Flexible Manufacturing Cell	FMC
22.	Distributed Computer System	DCS
23.	Automated Storage and Retrieval System	AS/RS
24.	Advanced Manufacturing Technology	AMT
25.	Special Purpose Machine	SPM
26.	Return on Investment	ROI
27.	Total Productive Maintenance	TPM

Sr. No.	Description	Abbreviations
28.	Supply Chain Management	SCM
29.	Structural Self-Interaction Matrix	SSIM
30.	Index of Performance	IOP
31.	Random Index	RI
32.	Consistency Index	CI
33.	Consistency Ratio	CR
34.	Reachability Matrix	RM
35.	Work in Process	WIP
36.	Multi-Objective Optimization By Ratio Analysis	MOORA
37.	Multiple Attribute Decision Making	MADM
38.	Dynamic And Proficient Manager	DPM
39.	Accurate Data And Information	ADI
40.	Multi-Functional Machines	MFM
41.	Valve Regulated Lead-Acid	VRLA
42.	Optimal Flow Path Layout	OFPL
43.	Flexible Fixture	FF
44.	Computer Aided Design	CAD
45.	Degrees Of Freedom	DOF
46.	Global Weight	GW
47.	Case Based Reasoning	CBR
48.	Genetic Algorithm	GA
49.	Rule Based reasoning	RBR
50.	Finite Element Method	FEM
51.	Advanced Manufacturing System	AMS
52.	Co-Ordinate Measuring Machine	CMM
53.	Total Weighted Interpretive Structural Modeling	T-WISM
54.	Compromise Ranking Method	VIKOR
55.	Type Of Machines	TM
56.	Setup Or Changeover Time	SUT
57.	Type Of Operations To Be Done On The Machine	TOM

Sr. No.	Description	Abbreviations
58.	Variety Of Parts/Products	VP
59.	Skills And Versatility Of Workers In The System	SVW
60.	Traffic Management Technique	TMT
61.	Positioning Of Idle Vehicles	PIV
62.	Battery Management	BM
63.	Capacity Of Buffer For The Vehicle	CBV
64.	Failure Management	FM
65.	Processing Time	PT
66.	Multi-Functional Teams	MFT
67.	Number of Parts Produced	NPP
68.	Lead Time	LT
69.	Motivational Schemes	MS
70.	Fixture Setup Time	FST
71.	Capacity of Pallets	CP
72.	Ease with which Parts can be Loaded or Unloaded from the Fixture	EPL
73.	Clamping Force required in the Fixture	CF
74.	Extremely Important	EI
75.	Most Important	MI
76.	Highly Important	HI
77.	Important and Necessary	I and N
78.	Important	I
79.	Multi- National Company	MNC
80.	Digital Signal Processor	DSP
81.	Flexible Numerical Control	FNC
82.	Pulse Width Modulation	PWM
83.	Open Architecture Controller	OAC
84.	THe Intelligent Numerical Control	THINC
85.	International Manufacturing Technology Show	IMTS
86.	Open Numerical Control System	ONCS

Sr. No.	Description	Abbreviations
87.	Personal Computer	PC
88.	Industrial Personal Computer	IPC
89.	Motion Preparation	MP
90.	Motion Control	MC
91.	Axis Control	AC
92.	Logic Control	LC
93.	Input/Output Drive	IODrv
94.	Structural Equation Modeling	SEM
95.	Fuzzy Weighted Interpretive Structural Modeling	F-WISM
96.	Flexibility	F
97.	Performance	P
98.	Fixture and Pallets	F and P
99.	Eigen Value	λ_{max}
100.	Self Guided Vehicle	SGV
101.	Segmental Flow-path Topology	SFT

CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

Flexible manufacturing system (FMS) technology is a revolutionary step that enables the industries in the current changing scenario to accommodate the rapidly changing customer requirements and maintain the rapid delivery of custom-made products. FMS has been adopted by industries to satisfy the rapidly changing demands of customized production (Kumar et al., 2006). It enables the industries to respond quickly to new opportunities and helps in attaining greater productivity and flexibility. FMS has been considered as a device to connect the gap between highly automated line and computer numerical control (CNC) machines. It is suitable for the mid-volume production of a variety of part styles with lots of benefits such as reduced set-up time, less work in process (WIP), short manufacturing lead time, higher machine utilization and improved quality.

The evolvement of FMS dates back to England (around 1960). The concept of FMS is credited to David Williamson, a British engineer during mid – 1960's under the name "System24", because it was believed that the group of machine tools comprising the system could operate 24 hours a day under computer control owing to early FMSs that were bulky and difficult to handle, having complicated material handling system (MHS) and consisting of numerous CNC machines. Earlier though the traditional FMS were highly mechanized, they were very costly and controlled by extremely complicated software. Also, there were only a few industries that could meet the expenses of traditional FMS. In late 1960's the first FMS was installed at Ingersoll-Rand company in Virginia. Germany implemented its first FMS in 1969, in cooperation with the University of Stuttgart. Russia and Japan implemented FMS in 1972. Over their evolution, the specialized components have been replaced by the more standard components. Japanese first introduced the standardization to the world and applied to general production.

The conglomeration of two or more CNC tools act as a flexible manufacturing cell (FMC), and two or more FMCs comprises an FMS. FMS is an integrated, computer controlled complex system of automated material handling devices and numerically controlled (NC) machine tools that can simultaneously process medium sized volumes of a variety of part types (Stecke, 1983).

FMS has the flexibility to exercise several non-identical part types at different machining centers simultaneously, and the variety and quantity of part types can be managed in response to the flickering demand requirements.

1.2 BASIC COMPONENTS OF FMS

The basic components of a flexible manufacturing system are (Groover, 2008):

- **Processing workstations:** In present day applications, to ease the process of the rapid physical changeover, processing workstations consists of CNC machine tools with automatic tool changing and tool storage features. These machine tools carry out machining operation on different part families. Machine tools play a very important role in determining the degree of flexibility and capabilities of an FMS. Machining centers are used for non-rotational parts, and for rotational parts, turning centers are used (Groover, 2003). Other workstations are load/unload stations, washing stations, and inspection stations, etc. as shown in Figure 1.1.

- **Material handling and storage system:** Primary and secondary MHS are widely used by most of the FMSs. The primary handling systems are used for transporting the workparts among different workstations in the system. The secondary MHS are responsible for transporting parts from the primary MHS to the workhead of the processing workstations or a supporting station and also for ensuring the accurate positioning of the workparts at the workstations. Material handling and storage system allow random, independent movement of workparts and sub-assembly parts between different processing stations. It enables handling of a diverse range of workpart styles, provides short-term storage, provides an easy mode for loading and unloading of workparts and creates compatibility with computer control (Groover, 2003).

- **Computer control system:** In FMS, a distributed computer system is linked to different workstations, MHSs, and other hardware components. Individual machines and components are controlled by a series of microcomputers which are further controlled by a central computer. Computer control system provides workstation control, distribution of control instructions to the different workstations, workpiece monitoring, MHS control, tool location control, tool life monitoring, performance monitoring and reporting, etc. (Groover, 2003).

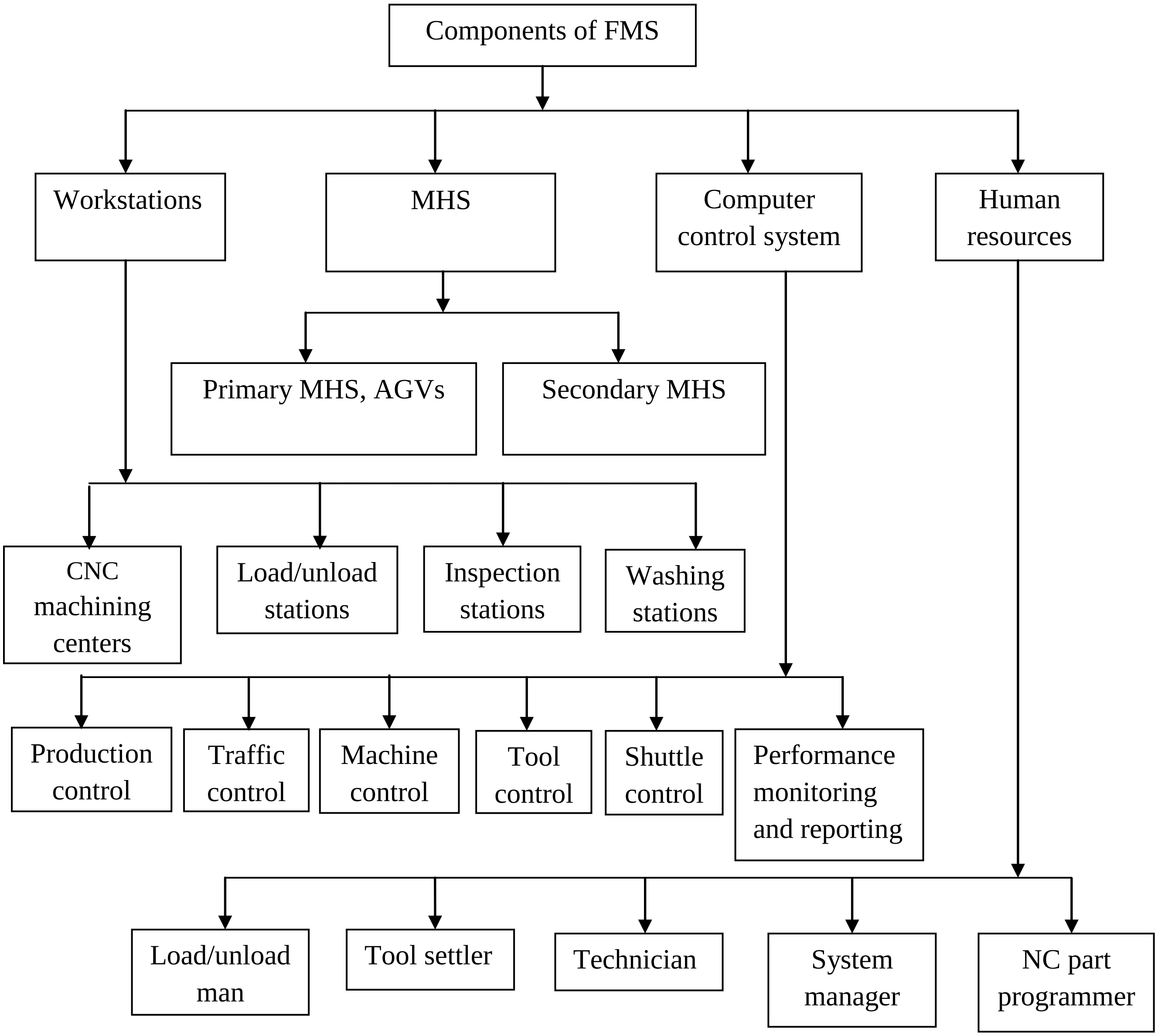


Figure 1.1 Basic components of FMS

- **Human Resources**: Even though an FMS is highly automated, people are required for performing a number of operations such as loading and unloading of raw material/finished products into/from the system, changing and setting of tools, machine tools repairing and maintenance, NC part programming, operating the computer system and overall management of the system (Groover, 2001). So, people are required to manage the overall operation and to perform a variety of supporting tasks in the system.

The need for flexible manufacturing has arisen to address high customized production requirements. An FMS seems to be the obvious solution for manufacturing constantly high quality and cost efficient goods. It can result in improvement of capital utilization, better quality, higher profit margins and increased competitiveness (Chen and Adam, 1991; Seidmann, 1993; Su, 2007; Singholi et al., 2010). To justify FMSs relatively high investment, it is of utmost importance to make full use of the flexibilities that the FMS offers. Efficient use of FMS provides the capability of optimizing various local and global performance measures for the manufacturing system, decreasing cost and increasing efficiency of the system (Ozmutlu and Harmonosky, 2005).

1.3 THE PRINCIPLE OBJECTIVES OF FMS

The current industry scenario requires reduction of inventories, quick market response time according to the changing market conditions, reduction in the cost of product and services as well as an increase in the market share. To meet these fluctuating requirements, industries are adopting FMS. The main objectives of using FMS are:

- To reduce the number of unmanageable variables.
- To reduce the direct labour cost.
- To minimize the problems due to poor co-ordination.
- To minimize the human intervention at the machining location.
- To minimize the dependency on highly skilled labours.
- To provide an opportunity for unattended production.
- To improve the responsiveness by process improvement, reduction in machine downtime, reduction in WIP and queue time, rapid physical changeovers, and fast delivery to customers, etc.
- To increase the flexibility of the system through:
    - Changing production volume
    - New product designs introductions and substitution in the existing part styles
    - Handling in variety of different part styles

- To increase machine tool utilization by reduction in machine downtime, waiting time and using automated features such as automated tool changers, etc.

1.4 MOTIVATION FOR FMS

The current business scenario demands the companies to be at a competitive advantage with their peers on producing high-quality products with cost efficiency and adaptation to the changing market environments. To achieve their goal according to the changing market conditions, they need flexibility in the way of performing different operations so as to satisfy different segments of the market. The innovation of FMS has provided flexibility to various industries, making them capable of handing out a diversity of workpart configurations simultaneously with the rapid tooling and physical changeovers. Flexible manufacturing has gained worldwide attention in recent years both in the manufacturing industry and academic research. In FMS, the production volume can be adjusted easily, according to the fluctuating demand requirements (EI-Tamimi et al., 2012). FMS assure 50% reduction in lead time and machining times using only a handful of machines and a few operators (Palframan, 1987). Numerous researchers have discussed the potential benefits from the implementation and utilization of FMS in their literature. A review of the literature reveals that there are many tangible and intangible benefits of FMS:

- It provides opportunity for unattended production
- It provides increased management control over the entire manufacturing process
- It enables to the machine and develops new workpieces at faster rates.
- It results in reduced scrap level by reducing errors, rework, repairs and rejections
- It reduces the lead time by 50% and improves the due date reliability
- It improves machine utilization by 30%, so fewer machines required
- It results in increased throughput
- It proves the facility of computerized monitoring
- It lowers the direct labor cost
- It provides reliable, consistent and good quality, due to the highly computerized monitoring and control
- It lowers the per-unit cost of products
- It results in reduction of WIP inventory

1.5 DESIGN ISSUES OF FMS

The FMS was welcomed in the industry owing to its cost efficiency, rapid turnaround, high quality, low inventory and low labour costs. FMSs have promised a plethora of benefits, but it is also accompanied with some difficulties with the implementation. Due to this, the implementation rate of FMS is much lower than has been expected (EI-Tamimi et al., 2012). The fundamental design issues, such as how large the system will be or the selection of processing and material handling equipment are usually dealt by arbitrary choice or back of the envelope calculations (Kouvelis, 1992). In literature, there are many issues concerned with designing of FMSs. Some of the important design issues related with FMS are discussed below:

- **Selection of equipment:** In the equipment selection problem, one needs to determine the optimal number and type of workstations and material handling equipment such as AGV's and robots in every cell for balancing the production line such that the total cost of production is minimized. Kusiak (1987) provided a framework using two integer programming models for the selection of equipment based on the integration of machine tools and material handling equipment. The basic objective in the equipment selection is that the parts are to be produced quickly with higher utilization of facilities. Some of the aspects that need to be considered during the selection of equipment are:
    - Nature of the material flow and bottle-neck operations
    - Production lot size and scheduling
    - Feasible production cycle time per pallet
    - Staffing level and the shifts required to meet the production goals

- **Layout design of FMS:** The layout design of FMS is an important issue, and the problems related to this issue must be solved at the starting of the system design. In FMS, the decisions associated with layout design cannot be taken independently because they influence other decisions also. The designer should analyze the different possible layouts and then should select the most suitable one for a particular case. For example, different machine tools in the system should be arranged in such a way that the material can be moved to various workstations in minimum time. Kouvelis and Kiran (1989) proposed different points that should be addressed during the designing of FMS layouts in comparison of conventional manufacturing systems. Kouvelis and Kiran (1988) discussed the effects of layout decisions on throughput rates. For the efficient utilization of FMS by solving the problems associated with layout design, an approach has been proposed by Afenakis et al. (1990). In his research, he also discussed the impact of MHS on layout design. Though a lot of work has been done in the area of layout design of FMS, following issues need to be addressed while designing the layout of FMS:

- Availability of space
- Number and capacity of the workstations
- Type and size of machine tools to be utilized
- Type of MHS to be used
- Number and capacity of the storage units or AS/RS system

- **Material Handling System:** The performance of the whole facility is directly affected by the performance of the MHS. As compared to FMS, there is much human intervention in traditional manufacturing system where human beings are involved in transporting the material between various workstations. The development of automated MHS and computer controlled MHS fully supported FMS. In the present scenario, mostly AGVs are used for material handling purposes. Mahadevan and Narendran (1990) addressed the issues involved in the design and operation of AGV based MHSs for an FMS. Ozden (1988) performed a simulation study on small FMS to consider the design parameters such as traffic pattern, the number of AGVs, the carrying capacity of each AGV and queue capacity of each machine. Guide path design is a critical issue and one of the very first problems to be considered during designing of AGVs. Some of the aspects that need to be addressed during the designing of MHS are:
    - Size of MHS
    - Automation level in MHS
    - Layout of machine tools
    - Space available
    - Number of such material handling devices
    - Material handling capacity of these devices

- **Labour issues:** According to Graham and Rosenthal (1986); Dunkler et al. (1988), the labour issues in FMS differ from those for conventional manufacturing systems in the following aspects:
    - There are no machine operators for individual machines
    - The set-up operations are performed by the machine itself or by robots
    - There is no manual material handling system
    - Layout job is supervisory in nature
    - The labour is multi-skilled in one or more tasks

Despite the increasingly important role of human-computer interface in an FMS, it is not clear which function should be allocated to the human and which should be allocated to the computer. Since labour unavailability and machine breakdown in FMS leads to a heavy loss in production, multi-skilled labour is preferred for FMS. Sharit and Elhence (1989) discussed the limitations of both human and computer in achieving both of these system performance objectives. But they did not offer any concrete framework for overcoming these limitations. Further, some points that need to be addressed during the labour issues are:

- Technical know-how of labour
- Advanced technical training of labours
- Availability of trained workforce
- Self-learning or attitude towards work
- Availability of multi-skilled labours

1.6 GAPS IN LITERATURE

Though FMS could offer a lot of benefits over the conventional manufacturing systems, it also poses a risk as the investment involved is very high and at times is not economically viable. An extensive analysis and elaborate designing of FMS is necessary before the implementation to avoid such expensive mistakes. An extensive literature review has been conducted to identify the gaps in the research area of FMS. A review of literature in the area of FMSs brings out the following gaps in the literature:

- The most important gap in the literature is the adaptation and implementation of FMSs in developing countries where labour is very cheap and easily available.

- Due to lack of universal acceptance of one definition, flexibility and its measurement have not been defined clearly in the literature.
- To optimize AGVs path layouts, very complex techniques have been used by different authors which are difficult to understand.
- In the literature related to the performance of FMS, not much work has been reported for modeling of FMS performance variables.
- In the exhaustive study of various research articles issues related to FMS design and planning such as loading, scheduling, material handling, etc. have been discussed but they are not addressed in a practical way.

1.7 RESEARCH OBJECTIVES

Based on the gaps in the existing literature, research objectives have been identified. These are as follows:

- Identification and study of different variables affecting machine, product and routing flexibility of FMS.
- Study and development of different performance measurement models for FMS.
- Design and Development of industry based optimization technique for AGV's path layouts.
- Design and Development of flexible fixture and pallets for handling a variety of parts.
- Study the alternate technologies other than CNC system in design and development of FMS.

1.8 ORGANIZATION OF PROPOSED THESIS

The present research work has been discussed in 11 chapters. The organization of research work has been depicted in Figure 1.2. The brief description of different chapters has been discussed as below:

Chapter 1: This chapter contains the introduction and principle objectives of FMS. Different components and design issues of FMS have been discussed. The motivation of this research, objectives of present work, gaps in literature in the context of Indian industrial environment, and organization of proposed thesis have also been discussed in this chapter.

Chapter 2: In this chapter, FMS has been classified, and literature review has been conducted in the domain of different issues related to FMS. Literature on various issues like planning issues, design issues, scheduling and control issues, operational issues, flexibility issues, performance issues, MHS issues, flexible fixture and pallet issues, justification of FMS and different variables affecting the design and development of FMS have been discussed. Some methodologies such as weighted interpretive structural modeling (W-ISM), graph theoretic approach (GTA), simple additive weighting (SAW), weighted product method (WPM), analytic network process (ANP), analytic hierarchy process (AHP) and 0-1 linear integer programming which have been used in this research work for making different models and frameworks have also been discussed.

Chapter 3: The development of a questionnaire for conducting a nation-wide survey to rank different factors affecting the design and development of FMS has been discussed in this chapter. The survey has been conducted mainly in medium and large-scale industries. The questionnaire included questions related to various aspects of FMS such as various factors affecting the machine, product, and routing flexibility, factors affecting the design and implementation of AGVs, factors affecting the performance of an FMS, factors affecting the design and development of flexible fixture and pallets. Observations and results of the survey are also discussed here.

Chapter 4: This chapter covers the identification and study of various factors affecting the machine, product and routing flexibility and development of W-ISM model for selecting the key variables affecting these flexibilities. The factors are analyzed by developing the interpretive structural modeling (ISM) approach, MICMAC analysis and by calculating the effectiveness index (EI).

Chapter 5: In this chapter, various measures and sub-measures affecting the FMS performance have been identified. The development of GTA, SAW and WPM integrated with AHP have been discussed for the prioritizing the performance measures. The performance measures such as measures related to finance, measures related to the customer, measures related to internal business, measures related to innovation and knowledge and operational measures are used for the analysis and among these the most important measure has been found out. The fuzzy logic used to change the qualitative measures into the quantitative measures has also been discussed.

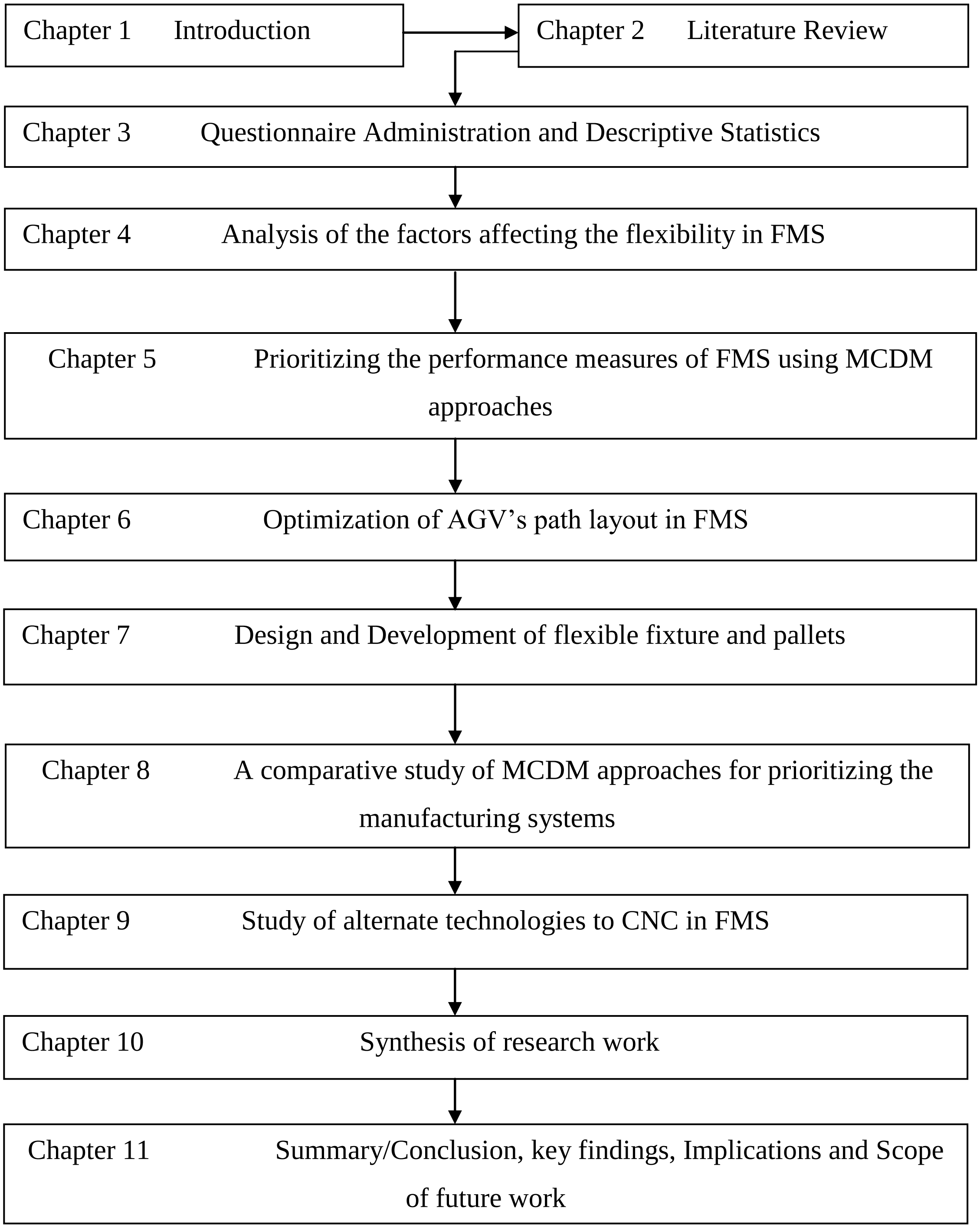


Figure 1.2: Organization of proposed thesis

Chapter 6: Various factors affecting the design and development of AGVs have been identified, various aspects related to AGVs such as guidance system, traffic management, dispatching system and safety features and the development of 0-1 Linear Integer Programming for optimizing the AGV’s path layout has been presented in this chapter.

Chapter 7: Various factors affecting the design and development of flexible fixture and pallets have been identified in this chapter. A case study has been discussed, and a design of pneumatically controlled flexible fixture and pallet has been proposed. A literature review related to different aspects such as components of the fixture, fixture system requirements, 3-2-1 locating principle, classification of flexible fixtures, fixture design process and computer aided fixture design (CAFD) along with some intelligent methods have also been discussed in this chapter.

Chapter 8: In this chapter, a comparative study of multi-criteria decision making (MCDM) approaches have been made for prioritizing the manufacturing systems among the FMS, humanized flexible manufacturing system (HFMS), computer integrated manufacturing (CIM) and CNC by analyzing the factors affecting flexibility, MHS, performance and the fixture and pallets. The objective was achieved by using ANP and AHP approaches.

Chapter 9: In this chapter, alternate technologies other than CNC system have been studied and identified for more convenient design and development of FMS.

Chapter 10: In this chapter, the synthesis of the research work as mentioned in the previous chapters has been presented.

Chapter 11: At last, this chapter contains a summary/ conclusion of the conducted research, research findings, key insights from survey and major implications of this research, limitations, and scope of further research.

1.9 CONCLUSION

This chapter presents the introduction and principle objectives of FMS. Different components and design issues of FMS have been discussed. The motivation of this research, objectives of present work and gaps in literature in the context of Indian industrial environment and organization of whole research work have also been discussed in this chapter.

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

Present scenario of the highly volatile market, which is influenced by global competition and changing customers' demands, has made the manufacturing companies look for new manufacturing systems which can fulfill their requirements for global competition (Sindhwani and Malhotra, 2016). Market globalization has forced the manufacturing industries to produce the goods with high-quality while maintaining low cost (Kaur et al., 2015). To survive in such a dynamic environment and to improve their competitiveness in term of quality, cost, and service, organizations are required to adopt such type of manufacturing system with the help of which flexibility and productivity can be achieved simultaneously (Kumar and Raj, 2014).

FMS is one of the options to enable the industries to compete in a global environment. So, a large number of industries are now adopting the mid-volume and mid-variety FMS instead of the conventional mass production (Dixit and Raj, 2016). FMS emerged as a powerful tool due to its wide flexibility, which is essential to stay competitive in this highly dynamic environment (Reddy and Rao, 2011). Flexibility is a very important aspect of FMS. The flexibility of a system is its ability to respond to changing demand patterns, so that the changes in the part mix and the quantity of production, can be adjusted quickly to meet changing requirements. There are some tests to check the flexibility of the system (Groover, 2008):

- Part variety test: whether the system is capable of processing a variety of workpart configurations in a non-batch mode or not?
- Schedule change test: whether the system is capable of accepting changes in the production schedule, part mix or production quantity?
- Error recovery test: In the case of machine breakdown, whether the system is capable of faster recovery not to interrupt the production completely?
- New part test: Whether the system is capable of introducing the new workpart designs into the existing part mix without much difficulty?

If a manufacturing system passes all four tests of flexibility, it is said to be a flexible one. An FMS passes all the four tests of flexibility. An FMS has been considered as a vital step towards the concept of the ‘factory of the future’ (Suri, 1984). It fills the gap between high-volume transfer lines and highly flexible manufacturing situations. FMS has been adopted by the industries to respond rapidly and efficiently to the unpredictable changes whether in goods market or processing techniques (Bi and Zang, 2001). An FMS addresses dynamic production needs and operations. It uses programmable machines integrated with an automated MHS under a central controller to manufacture a diversity of workparts of different batch sizes and quantities at non-uniform production rates (Leondes, 2003; Shivanand et al., 2006). FMS is one of the greatest revolutions in the manufacturing industries in the recent years due to its ability to produce a diverse range of workparts in less time and cost. The application of FMS in the current market scenario can satisfy the growing demands of variety, quantity, and speed at the same time (EI-Tamimi et al., 2012).

2.2 TYPES OF FMS

FMS can be distinguished depending on the number of machines and the degree of flexibility present in the system.

2.2.1 Depending upon Number of Machines: According to Groover (2008), an FMS can be distinguished into three types on the basis of the number of machines present in the system.

- **Single Machine Cell (SMC):** A single machine cell consists of one CNC machining center connected with a part storage system as shown in Figure 2.1. Completed parts are periodically unloaded from the part storage system, and raw workparts are loaded into it. It is capable of acting in response to variations in the production schedule, accepting new parts introduction and processing different part styles. It can operate in batch mode, flexible mode or a combination of both. In the case of CNC machine breakdown, the system stops. Thus, it satisfies only three of the four tests for flexibility.

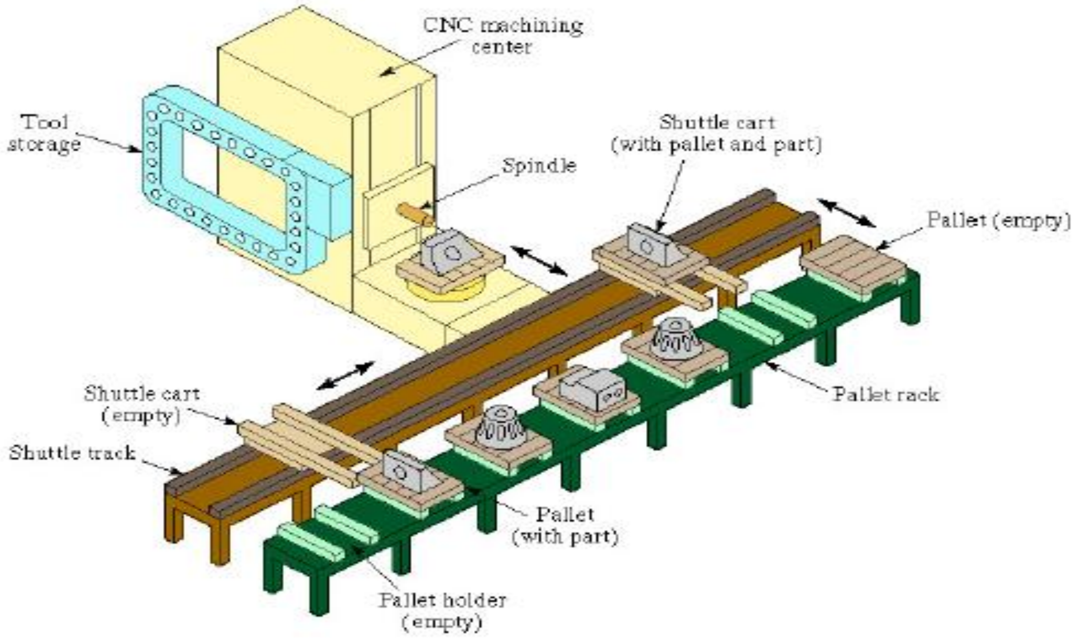


Figure 2.1: Single Machine Cell (Groover, 2008)

- **Flexible Manufacturing Cell (FMC):** FMC comprises of two or three machining centers and a part transfer system which is further linked to the loading/unloading station as shown in Figure 2.2. This cell can also operate in batch mode or flexible mode. It satisfies all the four tests of flexibility because, in the case of one machine breakdown, the parts can be processed on other two machines present in the system. According to Green (1986), “The FMC can handle a variety of configurations, but it generally has more than one processing station with some form of pallet-changing equipment, such as a robot or other specialized MHS. The FMC generally has a fixed process, and parts flow sequentially between operations. The cell lacks central computer control with real-time routing, load balancing, and production scheduling logic.”

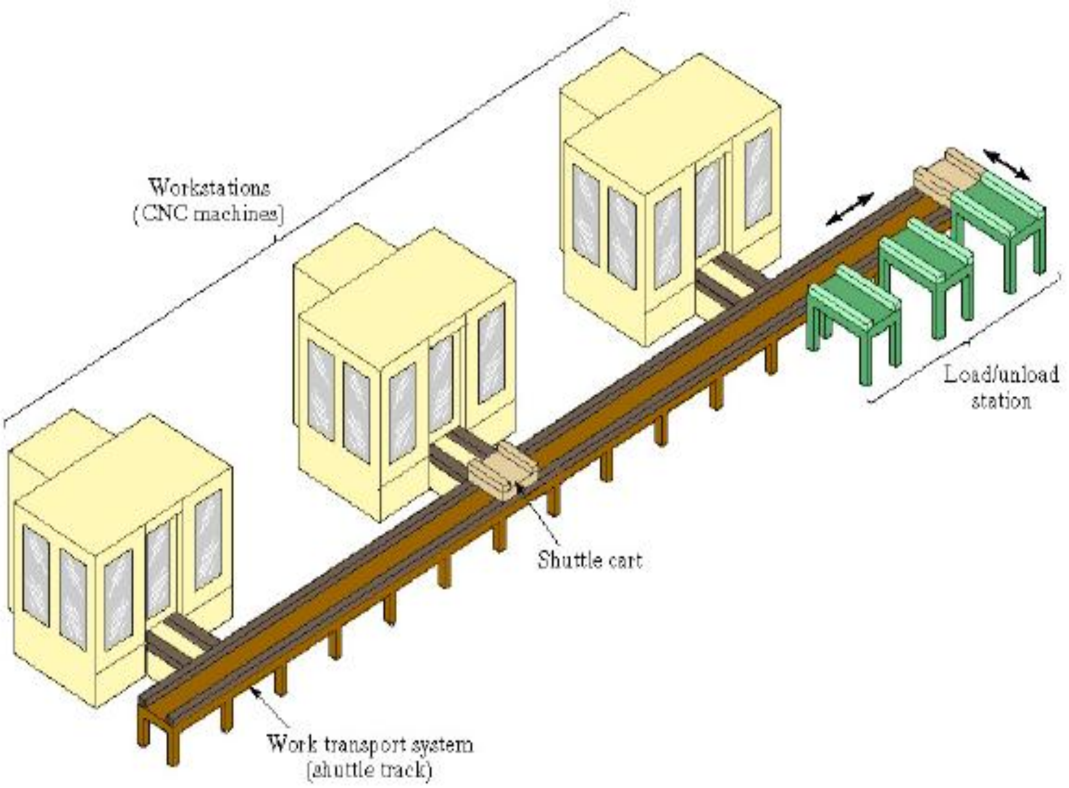


Figure 2.2: Flexible Manufacturing Cell (Groover, 2008)

- **FMS:** It comprises of four or more machining workstations (mostly CNC machine tools or turning centers) which are linked by a common part transfer system and controlled by a distributed computer system (DCS) as shown in Figure 2.3. FMS also comprised of a number of supporting workstations that helps in production but do not directly involved in it such as inspection stations, washing stations, co-ordinate measuring machines, storage stations, etc. This system satisfies all four tests of flexibility and here more sophisticated control is required because of the functions such as tool monitoring and diagnostic which are not present in the case of FMC. According to Green (1986), “The FMS is typically designed to run for long periods with little or no operator attention. Central computer control over real-time routing, load balancing and production scheduling distinguish FMS from FMC.”

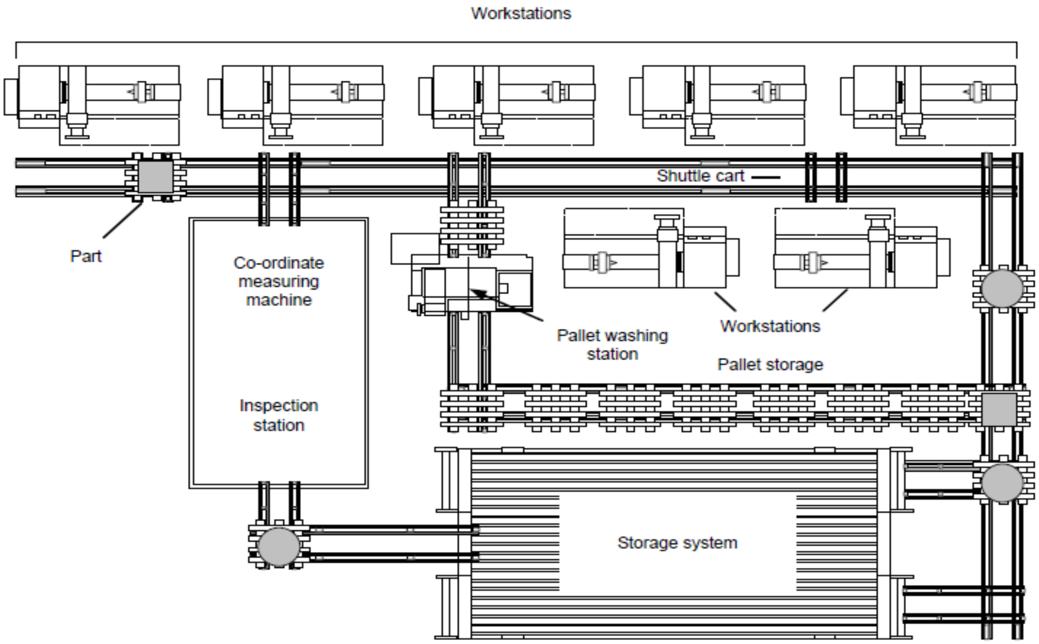


Figure 2.3: Flexible Manufacturing System (Groover, 2008)

In Figure 2.4, a comparison of three types of FMS classified on the basis of the number of machines present in the system as discussed above are shown by plotting annual production, flexibility and cost incurred against the number of machines.

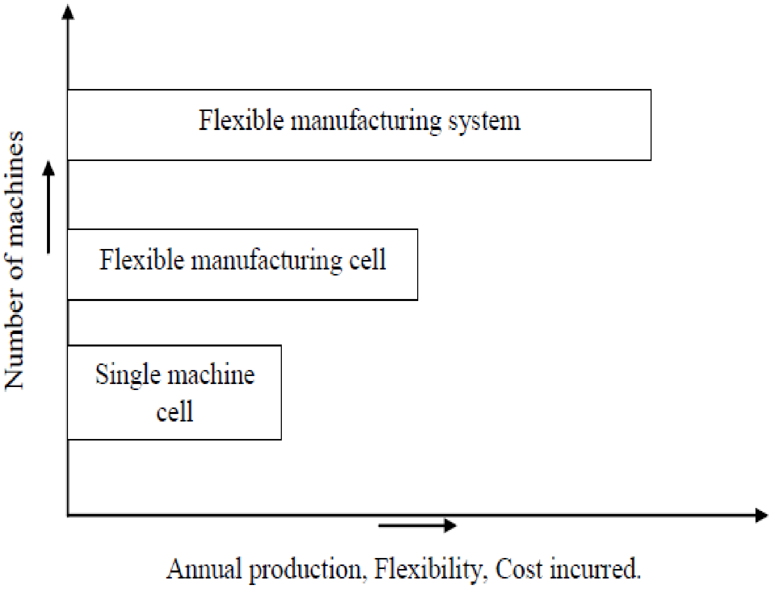


Figure 2.4: Comparison of three categories of FMS

2.2.2 Depending upon the Level of Flexibility: According to Groover (2008), another way of classifying the FMS is based on the level/degree of flexibility present in the system.

- **Dedicated FMS:** To produce a particular variety of parts, dedicated FMS is used. Here, the product design is considered stable and the part styles to be produced by the system are known in advance. In the case of dedicated FMS, the system is designed with a certain amount of process specialization and special purpose machines designed for specific processes can be implemented in the system for efficient operations.

- **Random Order FMS:** This type of FMS is proficient in processing large part families and parts having intricate shapes. Because of involvement of large part families, significant changes in part configurations takes place and to handle these changes, random order FMS must be more flexible than dedicated FMS. The production schedule is subjected to change from day-to-day, and new part designs will be introduced into the system. Therefore, the more sophisticated control system is required in this case.

  A comparison of dedicated and random order FMS is shown in Figure 2.5.

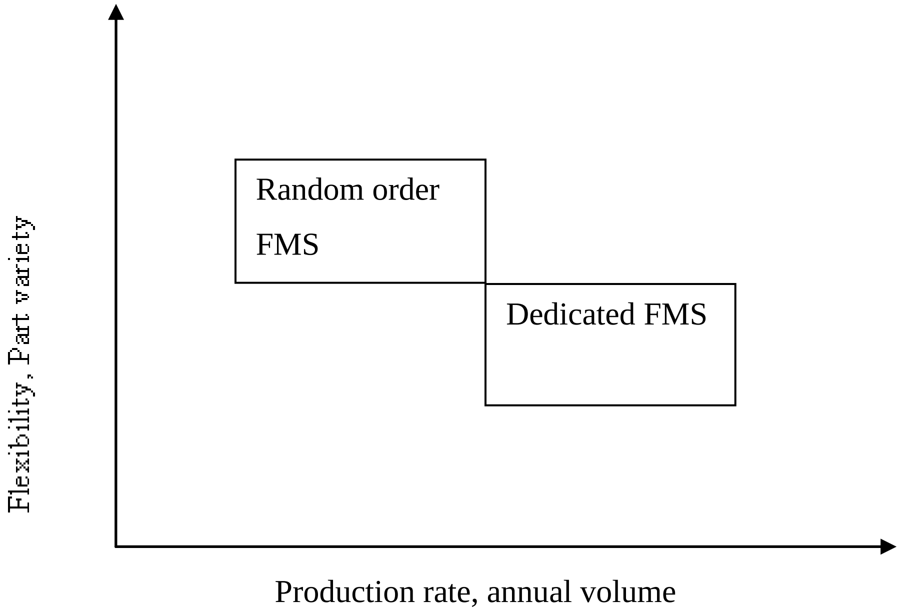


Figure 2.5: Comparison of Dedicated and Random order FMS (Groover, 2008)

2.2.3 Applications of an FMS

A large number of industries are now adopting FMS to compete for the fluctuating market conditions and to capture good market shares. However, accurate information about the extent of FMS installations throughout the machine-tool industry is a difficult task but, in almost all cases, successful applications of FMS results in higher machine utilization, improved quality, reduced labour and inventory costs and increased responsiveness to the changes in the marketplace, etc. Applications of an FMS can be found in various fields such as:

- Processing industry
- Sheet-metal press working
- Forging operations
- Assembly of parts
- Fabrication of sheet-metal
- Welding operations
- Electric industry
- Automobile industry
- Aircraft industry

2.3 PLANNING AND IMPLEMENTATION ISSUES IN FMS

According to Karande and Chakraborty (2013), selection of an appropriate FMS is a complicated task as it involves huge capital investment. Decisions regarding these investments become crucial for the survival of any manufacturing industry, due to tough competition in the globalized market. Implementing FMS has been motivated by the desire to respond more rapidly to dynamic changes both in demand and product mix. A company considering the installation of an FMS as a possible way of improving its productivity must decide, in a preliminary justification stage, whether this choice is appropriate to its situation or not. Successful FMS implementation results in decreased production cost, lead time, inventory, tooling, direct labor content, floor space, WIP and assembly (Saygin et al., 2001). To understand the issues related to the successful implementation of an FMS, a deep and careful study is required. Numerous authors have discussed various issues related to the implementation of an FMS in their literature, some of the issues are:

- According to Harvey (1984), major barriers to the efficient installation and implementation of FMS are financial, institutional, technological and related to human. Human and institutional barriers are related to communication and education, and they need to be discussed together.
- Fear of change is another issue related to the implementation of an FMS. Kiesler (1983) discussed this issue in his literature under the topic ‘impact of new technology in the work-place’.
- According to Scalpone (1984), lack of education in both management and technical staff is one of the major barriers to the successful implementation of an FMS.
- According to Kaighobadi and Venkatesh (1994), lack of top management commitment and support, lack of long-term and committed relationship with the vendors of both raw material and the FMS equipment, inadequate training and education of the personnel involved are other barriers to the implementation of an FMS.
- Solot (1990) classified the issues related to the implementation of FMS into four classes as mentioned below:

    - Due to the cost of all high technology equipment involved in an FMS, a careful study is required to choose during this phase. The configuration that is most appropriate to the production is to be obtained.
    - Once the system has been installed, the planning problems have to be tackled. These are the decisions that have to be made before the production can start.
    - Once the system has been set up for production, the scheduling problems have to be dealt with. They directly concern the running of FMS.
    - Finally, the controls problems associated with the real-time monitoring of the system have to be considered.

Stecke (1984) classified FMS issues into four categories: design, planning, scheduling and control and operational problems as discussed below:

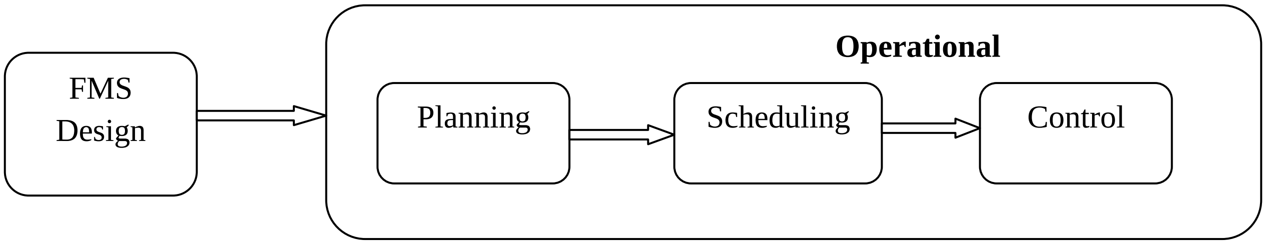


Figure 2.6: FMS Design

2.3.1 FMS Planning Issues

Due to the high investment required in FMS, higher resources utilization must be achieved, and this issue can be resolved by establishing a good production planning, scheduling, control and monitoring strategies. Major planning issues in designing of FMS are related with:

- **Selection of the range or families or part types to be produced on the FMS**: A family of part types to be produced and/or assembled on the FMS is determined among all the part types manufactured in an organization. FMS must be designed to process a limited range of part (or product) styles and boundaries of the range must be decided. Once the family of parts or part types are decided then the capacity of the system and functional requirements such as machining time, types and number of cutting tools required, etc. can be determined (Stecke, 1985). The selection of parts depends upon tool availability.

- **Processing requirements and selection of machine tools:** Arrangement of parts according to the processing requirements of each part to determine which workparts should be simultaneously processed and the numbers and types of technological equipment that should be used to process the parts are determined. According to Stecke (1985), each process plan not only describes which type of machine shall carry out each operation but also identify right cutting tools and cutting conditions. For example, non-rotational parts are produced by machining centers and rotational parts are machined by turning centers, etc.

- **Physical characteristics of the workparts:** Physical characteristics of the workparts are one of the major issues because the size and weight of the workpart determine the size of the machine to process the part and the material handling system needed to handle the part.

- **Production volume:** Type and quantity of the products which are to be made on FMS must be decided before starting production to determine how many machines of each type will be required. Once the production volume is determined then the type of MHS required to handle particular type and quantity of products can also be determined (Groover, 2008).

Some of the aspects that need to be addressed during FMS planning are:

- Financial condition/status of industry
- Type and number of parts to be manufactured
- Type and number of machine tools available
- Type and number of fixture and pallets available
- Space available
- Availability of technical and skilled labour

2.3.2 FMS Design Issues

The designing of FMS involves both physical and control aspects. According to Buitenhek et al. (2002), the physical aspects include the issues such as types and numbers of machines, MHSs, processing times on a machine, machine setting time, tool changing time, transportation time, loading, unloading time, tool storage, automated storage and retrieval system (AS/RS) capacity, the best possible layout and configuration, etc. and for the control aspects, the design involves defining the scheduling rules or algorithms that define the way the system is to be operated. In FMS design, there are some issues that need to be tackled as mentioned below:

- **Type of workstations:** According to the processing requirements of the parts, type and positions of workstations such as load/unload stations, processing stations, assembly stations, inspection stations, etc. must be decided.

- **FMS layout has to be determined:** The type of FMS layout and MHS chosen for the system directly affects the time taken in transporting the workparts from one machine to another. Therefore, they have a direct impact on the total system travel time.

- **Process routing variation:** Depending on the part processing variations, the layout must be decided. For example, if the part processing variations are minimal then in-line layout can be followed, but if part processing variations are high, then loop layout and open field layout should be considered.

- **Selection of the type and capacity of MHS:** The workparts in the FMS can be automatically transported via roller conveyors, two-way tow-line tracks, or wire-guided carts, etc. In the latter two cases, the number of carts has to be determined. According to the chosen layout, the primary and secondary MHS must be decided. Nowadays, the automated manufacturing systems are paying more attention towards AGVs because of their flexibility in transporting parts to various workstations present in the system.

- **WIP and type and size of the buffer:** Level of utilization and efficiency of FMS are affected by WIP, so it is an important issue of concern. Therefore, WIP allowed in the system should be determined. The buffer provides a queuing place for in-process inventory. If no area is provided for the buffer, in that case, WIP inventory remains on the MHS. Whether storage is centralized or local, the buffer size has to be determined and should be compatible with the level of WIP chosen.

- **Number and type of tools:** Type and number of tools required at each workstation for performing different operations based on the processing requirement of the workparts must be determined.

- **The number and design of the fixtures and pallets have to be determined:** Depending on the workpart shape and size, the level of WIP chosen, an appropriate number of pallet and fixtures must be decided. If the available fixture and pallets are less than required ones, in that case, the system is not efficiently utilized due to unnecessary part waiting time and if fixture and pallets are more than required ones, the system congestion as well as unnecessary expenses takes place.

A key element in the successful implementation is the quality of the design of the FMS. It is ironic that the most important decisions, those having the greatest long-term impact on the system are handled in the least careful manner. Therefore the design process must incorporate all those decisions, which lead to such an operational system. According to Kusiak (1985) and Stecke (1985a), they comprise the following:

- Selection of production system(s) used to manufacture the required products
- Selection of parts and the amount of them to be produced on an FMS over the whole lifetime of the system
- Selection of the equipment for the production system. For an FMS this includes:
    - Selection of the CNC machines, i.e., their type and number of each
    - Defining the number of load/unload stations in the system
    - Selection of the transportation, the material handling, and tool handling systems
    - Defining the number of buffers and the inventory system
    - Defining the number of pallets and fixtures needed
- Defining the type and structure of the planning and control system
- Defining the layout of the system
- Defining the number and skills of the personnel needed
- Defining the demand for and scope of each type of flexibility

Some aspects that need to be addressed during the design of an FMS are:

- Number and type of machine tools available
- Type and number of operations to be performed
- Number and variety of parts to be produced
- Number of tools available
- Capacity and type of MHS to be used
- WIP inventory
- Space available

2.3.3 FMS Scheduling and Control Issues

Generally, an FMS is expected to operate as an intelligent autonomous system that delivers products according to a dynamic strategy. However, achieving autonomy and intelligence in an FMS requires suitable co-ordination between scheduling and control tasks. Scheduling is defined as the allocation of resources over a specified time to perform a predetermined collection of tasks. Scheduling is the heart of the control system of an FMS (Liu and MacCarthy, 1996). Scheduling literature addresses a wide range of problems described with machine environment, job description and the objective function (French, 1982; Brucker, 1995).

The issues concerned with FMS scheduling consists of identifying the optimum input sequence of workparts, an optimum sequence at each machine given the current workpart mix, sequence of workstations because one operation can be performed on several workstations, sequence of material handling carriers because in AGVs the cart that must come to pick up a part has to be determined, the sequence of routes that must be followed by a cart to reach its destination. Machine scheduling problem and MHS scheduling problem particularly AGV scheduling problem have also been covered by the researchers in the literature. Spur et al. (1983) discussed a simulation approach to demonstrate the interaction between a number of AGVs, the vehicle speed, the number of pallets required, the buffer storage size, the vehicle waiting time and the part lead time. Cyrus and Kusiak (1984) used an integer programming approach for AGV scheduling problem.

The FMS control problem consists of determining strategies to react to unforeseen events such as machine breakdowns, monitoring the system to check whether the requirements and due dates are being met or not. The planning of the preventive maintenance operations is also considered as an FMS control problem (Stecke, 1985). According to Overmars and Toncich (1996), the control of an FMS is different from the control of other systems because it needs to fulfill the two independent sets of requirements. First, an FMS control is responsible for the actuation of the cutting tool and transporter movement associated with the various machine in the system. Second, the controller is responsible for scheduling parts to various machines and resolving the contentions that arise for available resources.

According to Solot (1990), the planning and scheduling problems are closely related, so they should be solved in an integrated manner. A similar remark has been made by De (1988). The planning-scheduling combination scheme structure is shown in Figure 2.7.

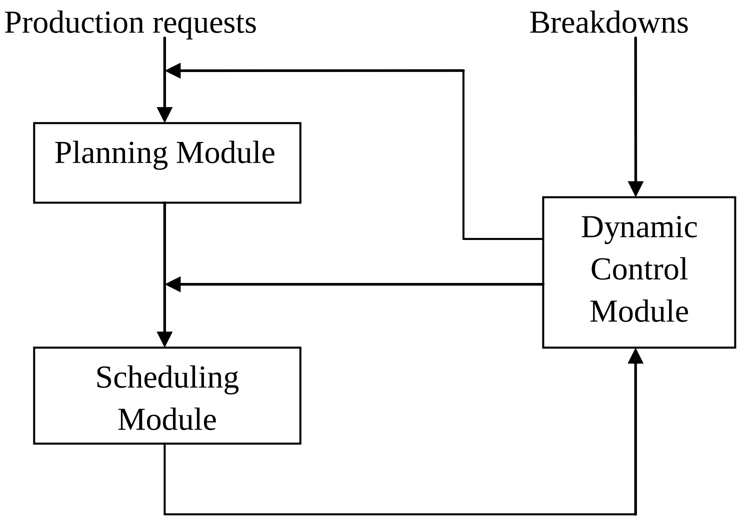


Figure 2.7: The planning-scheduling combination scheme (Solot, 1990)

The planning level is influenced by some exogenous factors. The production requests can originate directly from the customer orders or from the decisions taken by applying some inventory management policy. The decisions made at the planning level define the input level to the scheduling level. The events occurring during the running of the FMS are treated by a dynamic control module which decides whether the plan or the schedule should be recomputed. This module is also responsible for breakdown handling.

Some of the aspects that need to be addressed during FMS scheduling and control are:

- Part-quantity and variety to be manufactured
- Availability of machine tools
- Availability of tools and fixtures
- WIP inventory

2.3.4 Operational Issues

An operational planner of an FMS is usually confronted with issues arising out of the variation in customer orders, order arrival time, due date requirements and processing requirements. The operational issues are meant for taking the decisions associated with the planning, scheduling, and control of a given FMS. Stecke (1983) and many other authors, in order to manage the complexity of the problem, divided the FMS operational problem into two sub-problems: preproduction setup and production operation. Stecke (1983) emphasized on preproduction setup of the FMS. It has to be carried out frequently, as the part mix changes. There are some operational issues that must be monitored on a regular basis as discussed below:

- **Scheduling and dispatching:** Based on the master production schedule, scheduling of various activities must be done. In dispatching, parts must be launched into the system at the appropriate time.

- **Machine loading:** Machine loading problems are related to the allotment of different part types to different machine tools subjected to technological and capacity constraints and routing considerations of the FMS to meet certain performance measures. According to Kumar et al. (2006), machine loading involves the identification of a number of cutting tools to process various parts with the help of different equipment such as MHSs, pallets, jigs and fixtures and also determine how the parts should be allocated, so that optimal production can be reached.

- **Part routing:** Routes that should be followed by a part in the system must be determined by keeping in consideration the routes followed by other parts and tool management in the system.

- **Part grouping:** Part types having the similar processing requirements must be grouped for simultaneous production subject to the technological and capacity constraints of the FMS.

- **Tool management:** According to Reddy et al. (1990), tool management is an approach to resolve the problems related to different tool activities. Various problems are considered in tool management such as an arrangement for tool storage, resetting and loading of the tool, etc. Here, one must determine how to allocate tooling to different workstations in the system to ensure the right tool is available at the right place at the right time, to monitor the tool conditions and to identify how long each tool can last before replacement. When tools are operated for a long period, then tools are more prone to replacements because of constant wear and tear of tools.

- **Pallet and fixture allocation:** Different part styles require different pallet and fixtures, so pallet and fixtures must be allocated to each part type to be launched into the system. It is a pure assignment problem occurring at the physical level of the FMS.

Some of the aspects that need to be addressed during operations of FMS are:

- Number and variety of operation to be carried out
- Flexibility of the available MHS
- Tool magazine or tool turret capacity
- Type of tools available
- Workpiece material
- Method for loading/unloading of parts
- Process sequencing

2.4 JUSTIFICATION OF FMS

Flexible manufacturing is the least cost solution when producing a variety of parts using the same equipment. The cost benefits range from the high utilization of capacity to improved quality and low WIP inventory. The versatility of machines allows simultaneous production of multiple part types while maintaining high machine utilization (Shanker and Agrawal, 1991). Leimkuhler (1981) applied the traditional engineering economic approach to justify installing an FMS. This approach requires detailed information regarding parts to be manufactured and necessary machines. Hundy (1984) and Primrose and Leonard (1984) presented a qualitative approach to the FMS justification problem. According to Dornan (1987), an FMS can produce families of parts in random order, unattended and with little intervention.

Since approximately 75 percent of all metalworking manufacturing takes place in small to medium size batch production, justification of such automation has broad industry implications. FMS promises a plethora of benefits such as increased machine tool utilization, reduced WIP inventory, reduced number of machine tools, increased productivity of working capital, reduced labour costs, lower manufacturing lead times, high-quality products, less floor space required, increased flexibility, reduced setup costs, etc. (Palframan, 1987; Green, 1986). Through the study of literature regarding benefits of FMS, it can be concluded that though the implementation of FMS is a difficult task, but it can result in many benefits which are not possible by conventional manufacturing system.

2.5 DIFFERENT ISSUES CONCERNED WITH THE CURRENT RESEARCH

In literature, there are many issues concerned with FMSs. Some of the important issues in FMS concerned with the current research such as issues related to flexibility in FMS, performance measurement in FMS, MHS in FMS and fixture and pallets in FMS are discussed as follows:

2.5.1 Flexibility in FMS

System flexibility is the core subject of FMS concepts and practice. But this concept is not well defined. System flexibility is basically, how the system reacts to changes whether in the system or outside it. Flexibility is critical in effectiveness to manufacturing system allowing changes in parts assembly, variation in the process sequence, changes in production volume and changes in the design of the product. To deal with the current market situations, the FMS has become one of the most appropriate manufacturing systems because of its high flexibility. According to Gupta and Buzacott (1989), flexibility is the result of a combination of factors like physical characteristics, operating decisions, information integration and management practice and does not come from the abilities of the machines alone.

Numerous researchers have discussed FMS and its intrinsic characteristic of flexibility in their literature (Browne et al., 1984; Upton, 1994; Wadhwa and Browne, 1989). Considerable efforts have been made in describing and clarifying various notions of manufacturing flexibility along with possible ways to achieve them (Gerwin, 1982; Buzacott, 1982; Browne et al., 1984; Stecke and Browne, 1985; Jaikumar, 1986; Lim, 1986, 1987; Slack, 1987; Sethi and Sethi, 1990). In literature, a number of flexibility measures have been defined and suggested by numerous researchers, but no guidance has been provided to compute these measures (Soon and Park, 1987; Brill and Mandelbaum, 1989). Although numerous authors have shown wide interest, flexibility has still remained inadequately stated in theory and inefficiently utilized in practice (Beskese et al., 2004). To avoid confusion, some important type of flexibilities must be focused.

Browne et al. (1984) and Buzacott (1982) attempted to divide the general term ‘flexibility’ into a number of elementary concepts. Buzacott and Shanthikumar (1980); Browne et al. (1984); Swamidass (1988) and Kusiak (1986) proposed various types of flexibilities, but within the scope of present research, only three type of flexibilities (machine, routing, and product flexibility) are considered. Machine flexibility is the ability of a machine tool to perform a diverse range of processing operations on different workpart types. Product flexibility is the capability to adapt new product designs with relative ease in order to respond quickly to the changing market requirements. Routing flexibility is the ability to process workparts on alternative machine tools in case of equipment breakdowns, tool failure and other disturbances caused at any particular workstation (Sethi and Sethi, 1990; Azzone and Bertele's, 1989).

There are various factors which affect these flexibilities. Therefore, there is need to find out the factors affecting these flexibilities and their importance. Some of the important factors identified with the help of literature review, questionnaire-based survey and discussion with the experts' both from industry and academia are:

- Types of machine
- Maximum number of tools available
- Maximum number of operation available
- Tool magazine or tool turret capacity
- Tool changing time
- Type of operations to be done on machine
- Variety of parts to be handled by the machine
- Setup or changeover time
- Skills and versatility of workers in the system
- Design changes required in the product
- Variety of products
- Offline part programming preparation facility
- Number of existing part families matching the new product design
- Machine flexibility
- Number of machines available in the system
- Maximum number of routes available
- Similarity of workstations
- Space availability
- Availability of technical know how
- Flexibility of MHS
- Similarity of parts in the system

2.5.2 Performance Measurement in FMS

Performance measurement is a vital issue in FMS. In today's highly competitive business environment, survival and growth of manufacturers depend on their ability to offer a great variety of high-quality products at an acceptable price using minimum lead time (Singh and Ahuja, 2015). Cost reduction without compromising on quality has become the motive of each manufacturing industry, to remain viable in the global market (Sundharam et al., 2013). The idea of FMS is to get an edge in comparison to other industries by improvisation in production and quality (Rao and Deshmukh, 1994).

A lot of efforts have been employed by the researchers to find some robust schedule that can give optimum performance measures of FMS, without much affected by the uncertainties prevailing in the system (Verma et al., 2011). In recent studies, researchers have paid their attention to improve the FMS performance (Wadhwa et al., 2005; Chan, 2003). Singholi et al., (2012, 2013) discussed the effects of manufacturing flexibilities on the performance of an FMS. They used the Taguchi experimental design methodology for evaluation of varying levels of machine and routing flexibility on the performance of FMS. FMS performance is influenced by the type of MHS chosen for the system. Thus, when designing an FMS, decisions should be made based on the MHS being used. Most of the performance measurement models discussed by the authors in their research work involve the use of complicated algorithms and methodologies, which make it very difficult to understand the model. This is the thrust area which must be focused in research.

2.5.3 Material Handling System in FMS

Material handling is of prime importance in an FMS because material spends more than 80% of the time on a shop floor either in waiting or in transportation (Singh et al., 2016). According to Tompkins and White (1984), about 20–50% of the total operating cost of manufacturing facilities can be attributed to material handling costs. To achieve availability and non-accumulation of materials at workstations, there is a need for less congestion, reduced idle time of machines and timely delivery i.e. efficient material handling. To reduce wastage, breakage, loss and rejection, etc., safe handling of materials is required. In recent years, due to the advancement of automation and control technologies, automated material handling systems are used by modern factories to perform their material handling operations. Robots, conveyors, AGVs, monorails and other rail guided vehicles and other specially designed vehicles are some of the material-handling equipment used in FMS.

Among them, AGVs are well known for their routing flexibilities and programmability. In modern manufacturing systems, AGVs have become an integral part of MHSs because of their high flexibility, the guide path can be easily modified to respond to any changes in the FMS where routine changes are inevitable (Azimi, 2011). According to Vis (2006), the development in AGVs technologies has improved the flexibility and autonomy. Due to advanced features of AGVs such as better routing flexibility, safety, better space utilization, etc., they have been considered as one of the most efficient ways for transporting material between different workstations (Erol et al., 2012). To avoid collisions with each other and complete their tasks, AGVs need to be coordinated along the roadmap itself (Parker, 2009). Graphs of the several layers are used for searching the path.

The performance of the overall system is greatly influenced by the guide path layout since it has a direct impact on the travel time, on the installation costs, on the complexity of the control system software and efficiency of vehicle dispatching and scheduling. The researchers in the last few years have paid much attention to the AGV path design problem, and a lot of work have been done with different techniques to find out the optimum path layout which is quite complex. Therefore, some techniques must be studied and analyzed to optimize the AGV path layouts which are easy to understand and implement in real world FMS.

2.5.4 Flexible Fixtures and Pallets in FMS

To remain viable in the current market scenario, every manufacturing industry has been making efforts to sharpen its rivalry by making improvements in the products quality, reduction in the manufacturing lead times to bring new products to the market and squeezing the production costs. In order to make the efficient and low-cost fixtures, the fixture design methodologies should be upgraded (Wang et al., 2010). Dedicated fixtures are designed for the specific products. Therefore, one of the major problems with custom-oriented dedicated fixtures is that they cannot be used with the workparts or assemblies having different shapes and sizes, they are also time-consuming and costly to build (Bi and Zhang, 2001).

The fixtures have a direct impact on the product manufacturing cost, product quality, production volume and the static and dynamic rigidity of the product. According to Hashemi et al. (2014a), to lower the cost and the lead time associated with the fixture design, there is a strong desire of computerization and automation of fixture designs. According to Newman et al. (1991), the use of general purpose pallets increases the overall flexibility of the system both regarding new product introduction as well as scheduling of actual mix of parts to be processed. Fixture decreases the expenses involved with the quality control of processed workparts as it opens the door for consistent quality in manufacturing and increases the versatility of machining operations to be performed (Liu, 2004).

An accurate fixture design is critical for quality of a product based on accuracy, precision and final product of the designed parts. Fixture design is under the combined influence of workpiece specifications, machining methods, material performances, etc. It demands rich experience of the designers, which leads to a significant increase in the design cycle time and costs (Hashemi et al., 2014b). If the designer is aware of more standard locating and clamping strategies then he would be able to make more creative designs (Pachbhai and Raut, 2014).

A poorly designed fixture may result in over-clamping and excessive vibrations, this leads to dimensional inaccuracies, reduced surface quality and separation between the workpiece and fixture, causing the part to be released, ultimately damaging the processing station, halting the production and even injuring the personnel sometimes (Bakker et al., 2012).

2.6 IDENTIFICATION OF FACTORS RELATED TO DIFFERENT ISSUES IN THE CURRENT RESEARCH

With the help of literature review, questionnaire-based survey and discussion with the experts both from the industry and academia following factors were identified related the different issues in the current research.

2.6.1 Identification of Factors affecting Machine, Routing and Product Flexibilities

Following factors are identified which affect the machine, routing and product flexibilities:

- **Set-up or changeover time:** In order to machine various part types speedily i.e., faster customer delivery, reduction in set-up time and subsequently in manufacturing lead time is required. Set-up time of a machine can be defined as the amount of time spent in performing various tasks such as fixture setting, calculating the tool offsets, etc. to change from the last part of a production lot to the first part of the next production lot. To reduce the set-up time, FMS are equipped with CNC/NC machine tools which have automatic tool interchange capabilities (Chan, 1999). So, FMS helps in the process of rapid changeover.

- **Tool magazine or tool turret capacity:** FMS has the capability of managing a diverse range of part type with different configurations and the production of these part styles requires a series of operations (Groover, 2003). Complex parts may require numerous processing steps and a number of cutting tools are required for performing these operations.CNC machine tools in FMS are generally equipped with large tool magazines to hold several cutting tools to perform various operations on a variety of parts. Duplication of the most often used tools in the tool magazines is allowed to ensure the least non-operational time.

- **Skills and versatility of workers:** More skilled and versatile workers means more flexibility of FMS. If the workers are skilled and they know multiple and better working techniques, then they can understand and solve the problem faced by them during operations in less time (Raj et al., 2008a). If the workers with high cognitive skill and the ability to follow instructions are available, then it will be helpful for the industries (Cardy and Krzystofiak, 1991; Cordero, 1997). Cognitive ability helps them to understand the expert system, programming, and limitations of FMS.

- **Types of the machine:** Various types of machine tools like CNC machines and machining heads in special purpose machines (SPMs), etc., are used in FMS. Machine tools are the main component of FMS. It has been reported in the literature that CNC machines are the basic component of FMS because of their softwired nature. According to Browne et al. (1984), the flexibility of a machine depends on the ease with which changes can be made to process a given set of part styles. Greater the range of operations and part styles a machine can handle, the greater will be the flexibility of that machine.

- **Variety of parts to be handled by the machine:** Flexibility of a manufacturing system depends on the capability of processing a variety of part types. FMS are well known for their capability to process a diverse range of part types efficiently (Sujono and Lashkari, 2007). The flexible automated system is competent in handling a range of part types with almost no time lost in switching from one part type to the other (Bayazit, 2005).

- **Space availability:** The optimal arrangement of equipment and machine tools in the available space is one of the vital desires in the designing of FMS for its efficient operation and low operating costs (Ficko et al., 2004). The arrangement of operational equipment and other facilities are dependent on the type of production. For example, AGVs are used as an automated material handling system in FMS. If the machines are not located properly, then more AGVs will be required and due to congestion caused by them, AGVs will be utilized insufficiently. So, in the FMS, the devices and machines must be arranged in a best possible way to properly utilize the available space to enhance the overall flexibility of the system.

- **Tool changing time of the machine:** In FMS, machine tools are used to perform various types of operations on different workpart types. To perform these operations, a number of tools are required that must be changed in switching from one operation to another. To accomplish the process of tool exchanging between the machine tool spindle and tool magazine, an automated tool changer is used under the control of NC program. These tool magazines can handle a number of cutting tools ranging from 16 to 80 (Filote and Ciufudean, 2010).

- **Design changes required in the product:** If a particular manufacturing system has the capability of handling a variety of new and unpredictable part designs then, its flexibility will be more. With the changing demands of the customers on a daily basis, changes in the product design are frequently required. According to Primrose and Verter (1996), an FMS results in the introduction of new products. FMS have the capability to produce a wide range of products and have the ability to cope with fluctuations in demand and uncertainties efficiently. FMS are acknowledged for their potential to respond rapidly to part-mix changes (Sujono and Lashkari, 2007).

- **Flexibility of material handling system:** For loading/unloading the materials from one machine to another machine and to pick and drop the material, AGVs and industrial robots are used. This results in increasing the overall efficiency of the system by reducing the human intervention and human inaccuracy. Automated material handling devices enhances the overall efficiency of the facility by reducing the lead time, WIP and inventory level (Spano et al., 1993). So, greater flexibility is added to the manufacturing system with regard to material handling, volume, routing, and delivery (Rao and Deshmukh, 1994).

- **Maximum number of routes available:** In the case of machine breakdown, routing flexibility allows the system to continue processing a set of parts types with alternate routes. Routing flexibility is seen as not only a way to cope with machine breakdown but also a means to improve the performance and flexibility of a manufacturing system (Chung and Chen, 1989, 1990). So, more number of routes available reduces the non-operational time and enhances the flexibility of the manufacturing system.

- **Type of operations to be done on the machine:** Each machine used in an FMS has high flexibility and capability to carry out different operations on various part styles simultaneously. Each workpart may have different processing requirements such as milling and drilling operations, etc. For machining non-rotational parts, CNC machining centers are used and for rotational parts turning centers are used. If there are requirements for multi-tooth rotational cutters then milling centers are used (Groover, 2003).

- **Offline part programming preparation facility:** Implementing the offline program system saves valuable machine time, leaving the machine to utilize most of its time in operational activities. In industry, the ability to prove out CNC part programs away from the machine in a clean and quite environment and store program on disk media has many obvious advantages. This facility improves the throughput by reducing the non-operational time of the machine and maximizes the output. FANUC offline software is very important for both educational and industry level. Unexpected scenarios which intensify the programming requirement for the CNC can be addressed better with the aid of offline programming because multiple parts can be programmed across computer terminals for the same machine (Anand, 2012).

2.6.2 Identification and Categorization of Performance Measures in FMS

Owing to the high cost of capital investment in the FMS, the performance measures are quite complex and often involve multiple objectives. In addition, these objectives may differ from system to system depending upon system configuration, type of parts to be produced, demand conditions, etc. (Stecke, 1983). With the help of literature review and discussion with the manufacturing managers and academicians, it has been found out that there are various factors which could affect the performance of the FMS. Therefore, it is very much essential to anticipate the problems related to it. Hence, it becomes necessary to identify and analyze these factors affecting the performance of the FMS. These performance measures have been grouped into five major categories:

2.6.2.1 Measures related to Finance

These measures are related to the economic aspects of FMS. Kumar et al. (2006) suggested that as due to the high cost involved with FMSs, they should be handled efficiently in order to achieve the desired goals with less investment risk. Due to the limited financial resources in developing countries like India, these factors are vital. It may occur due to the lack of investment capability, the cost associated with FMSs equipment, poor rate of return on investment, high taxes like sales tax, high-profit margins, the poor cost of sold goods, etc. Performance measures related to this category are:

- Return on investment (ROI)
- High-profit margins
- Costs of sold goods
- Growth in market share

2.6.2.2 Measures related to Customers

Nowadays, demands and requirements of the customers changes speedily, they want good quality products at the lowest possible cost. In order to be competitive, the manufacturing industries should accommodate these changes as fast as possible. Customer satisfaction is the concept of how well the current customers are utilizing the company’s products and what their feelings are about its services (Simchi-Levi et al., 2004). To understand customer satisfaction, it is necessary to understand the customer expectations and perceptions and customer value.

Customer perceptions of service quality may be different to that of management, and this can lead to the development of measures of internal business process within the organization, which are drivers of customer perceptions and satisfaction (Lovelock et al., 2001). Performance measures related to this category are:

- Life of product
- Customer satisfaction
- After delivery services
- Maintenance cost
- Cost of product

2.6.2.3 Measures Related to Internal Business

To be consistent with the research findings which indicate that minimizing the WIP inventory and maximizing machine/system utilization are two of the most important FMS performance criteria (Smith et al., 1986; Stecke and Kim, 1988). Therefore, it is essential and practical to incorporate these two criteria as performance measures of the FMS. Reduction in set-up time, the capability of handling a variety of workparts efficiently and simultaneous production of several part types, results in higher machine utilization (Bayazit, 2005). Reduction in scrap is possible if inspection is included into the manufacturing process to permit the corrections to be made to the process as the product is being manufactured (Groover, 2003). The throughput time could also be reduced by reducing the queues time, waiting time and inspection time. Performance measures related to this category are:

- Reduction in WIP and queues
- Assets utilization
- Flexible environment
- Throughput time
- Reduced waste

2.6.2.4 Measures related to Innovation and Knowledge

The operational guidelines of the firm are decided by both business philosophy and the top managements' personal philosophy. The purpose must be clearly and continuously communicated to all personnel. Absence or minimal support from the chief executive officers, management and administrators can affect the performance of the FMS. A demonstrated leadership to address the challenges ahead in the business activities of the enterprises is considered necessary to provide a clear vision. The quality initiatives are taken by the leader and leader stability can only lead to unfavorable outcomes (Rad, 2005). Lack of collaboration between divisions is one of the most critical performance measures, so the accurate data and information must pass to each department for the efficient operations of the organization. In order to make the correct and appropriate decisions, correct and reliable information or data should be provided to decision makers (Masters, 1996; Rad, 2005). The system should be flexible enough so that new products and new processes could be introduced into the system. Performance measures related to this category are:

- Awareness of challenges ahead
- Dynamic and proficient management
- Product innovation
- Process innovation
- Accurate data and information system

2.6.2.5 Operational Measures

Performance is directly related to a number of new and unpredictable products handled by a particular manufacturing industry in short lead time and at lower costs. Bayazit (2005) stated that flexible automated system is competent in handling a diverse range of parts types with almost no time lost in switching from one part type to the other (Bayazit, 2005). Groover (2003) proposed that in an FMS, during the reprogramming and changing the physical set-up such as tool changing, fixtures and machine settings, etc., no production time is lost. It results in reduced set-up time and programming time, which leads to lower manufacturing lead time and less WIP. Nagarjuna et al. (2006) has proposed that the ability of FMS to attain the flexible automation distinguishes it from other industrial automation technologies. Chung and Chen (1989, 1990) stated that the routing flexibility is seen as not only a way to cope with the machine breakdown but also a means to improve the performance of a manufacturing system. Performance measures related to this category are:

- Processing time
- Type and number of operations

- Routing flexibility
- Multi-functional machines
- Number of parts produced
- Lead time

2.7 METHODOLOGIES USED IN THE PRESENT RESEARCH WORK

Different techniques which have been used in current research for the analysis of different measures/factor affecting various issues in FMS are:

- Weighted Interpretive Structural Modeling (W-ISM) Technique
- Graph Theoretic Approach (GTA)
- Analytic Hierarchy Process (AHP)
- Simple Additive Weighting (SAW)
- Weighted Product Method (WPM)
- Analytic Network Process (ANP)
- 0-1 Linear Integer Programming

The above mentioned methodologies are discussed below:

2.7.1 Weighted Interpretive Structural Modeling (W-ISM) Technique

W-ISM has been used to identify the relationships among the different factors affecting the flexibility in FMS. It is the combination of ISM and EI. The theoretical foundation of W-ISM technique has been developed by Chand et al. (2014, 2015) derived from ISM. W-ISM is the extended version of ISM. Here to calculate the EI, some weight is assigned to each factor based on the criteria. Chand et al. (2015) used the W-ISM technique for analyzing the competitiveness of uncertainty and risk measures in the supply chain. Chand et al. (2014) analyzed the operational risks in the supply chain by using W-ISM technique.

Warfield (1973) introduced the ISM approach to analyze the complex socioeconomic systems and Malone (1975) conducted a brief review of the ISM. In this approach, all the factors and their interrelationships are decided by the group judgments. Therefore, it is known as ‘interpretive structural modeling’. ISM is a well-established methodology for determining the relationships among specific elements, which define a problem or an issue (Jharkharia and

Shankar, 2005). ISM is a powerful methodology, which can be useful in several fields (Bolanos et al., 2005; Faisal et al., 2006, 2007; Jharkharia and Shankar, 2004; Qureshi et al., 2007; Singh et al., 2003; Thakkar et al., 2007, 2008). It is considered as a modeling technique because the relationships between different factors of a system and overall structure have been shown with the help of a digraph model. This, in turn, helps in enforcing order and direction on the complexity of relationship among different factors of a system (Singh et al., 2003). From the literature review, applications of ISM discussed by numerous authors are shown in Table 2.1.

Table 2.1: Brief review of ISM applications

S.No.	Authors	Applications
1	Panahifar et al. (2014)	Utilized ISM approach for the analysis of CPFR implementation barriers
2	Azevedo et al. (2013)	Used this technique to identify and rank performance measures: An application in the automotive supply chain
3	Attri et al. (2013a)	Applied the ISM approach for identifying and analyzing the mutual interaction of the factors in the implementation of Total Productive Maintenance (TPM)
4	Shahabadkar et al. (2012)	Used deployment of ISM in supply chain management (SCM) - An overview
5	Raj et al. (2012)	For modeling the factors affecting flexibility in FMS
6	Nagar and Raj (2012b)	For the analysis of critical success factors for implementation of HFMS in industries
7	Nagar and Raj (2012a)	Utilized ISM approach for risk mitigation in the implementation of Advanced Manufacturing Technology (AMT’s): A guiding framework for future
8	Mishra et al. (2012)	Used the ISM methodology for determining the interrelationship of drivers for agile manufacturing: an Indian experience

S.No.	Authors	Applications
9	Singh (2011)	Used this technique for developing a framework for the coordination in supply chain of SMEs
10	Hans et al. (2011)	Used this technique for modeling of supply chain risks
11	Subramanian et al. (2010)	Utilized ISM approach for analyzing the buyer-supplier relationship factors: an integrated modeling approach
12	Mudgil et al. (2010)	Used this technique for modeling the barriers of green supply chain practices
13	Tabrizi et al. (2010)	Used ISM to determine the relationships among knowledge management criteria inside Malaysian organizations
14	Raj et al. (2009)	Used this technique to analyze interaction between barriers of transition to FMS
15	Raj et al. (2008a)	Used this technique for modeling the enablers of FMS: the case for India
16	Singh and Kant (2008)	Used ISM for analyzing the knowledge management barriers
17	Singh and Garg (2007)	Used ISM for improving the SMEs competitiveness
18	Faisal et al. (2006)	For the analysis of risk mitigation in supply chain
19	Ravi and Shankar (2005)	For the analysis of interactions among the barriers of reverse logistics
20	Bolanos et al. (2005)	Used ISM in strategic decision making
21	Singh et al. (2003)	Used this technique for the implementation of knowledge management in engineering industries

The various steps involved in the ISM technique are:

Step 1: Factors which are related to the problem are identified with the help of a questionnaire-based survey. Establish a contextual relationship among factors with respect to which pairs of factors would be examined.

Step 2: A structural self-interaction matrix (SSIM) of factors is developed which indicates the pair-wise relationship among factors of the system. This matrix is checked for transitivity. Transitivity of the contextual relation is a basic assumption in ISM which states that if element A is related to B and B is related to C, then A is related to C.

Step 3: With the help of SSIM, a reachability matrix (RM) is developed.

Step 4: The RM is partitioned into different levels.

Step 5: From the RM, a conical matrix is developed, i.e., with most zero (0) elements in the upper diagonal half of the matrix and most unitary (1) elements in the lower half.

Step 6: Based on the relationships obtained in the RM, a digraph is developed, and transitivity links are removed.

Step 7: The final digraph is then converted into an ISM model by replacing factor-number nodes with the statements.

Step 8: The model is reviewed to check for conceptual inconsistency and making the essential modifications.

For computing the EI, the mean score with their ranks of different factors affecting flexibility is calculated. After this, inverse rank and weight of each factor are found out. For assigning the weights to different factors, the highest and lowest value of five points Likert scale i.e., 5 and 1 are mapped 100% and 0% respectively. The criteria for weight (W_i) is as under:

W_i = +1 (Strength), when percentage score > 60%
= 0 (Neutral), when percentage score is between 40 – 60%

= -1 (Weakness), when percentage score < 40%. This framework was given by Cleveland et al. (1989) with $C_j = (W_i * \text{Log} K_i)$.

2.7.2 Graph Theoretic Approach (GTA)

In this research work, GTA has been utilized to find the performance index value for any industry which is interested in improving their performance. Due to the complexity of the relations between various performance measures of a manufacturing system, it is very difficult to assess them. An appropriate methodology should be used to handle such a situation. The selection of appropriate technology that achieves the organizational objectives must be made by sound decision (Mamalis, 2005). Digraph and matrix approach has the capability to tackle such a complex situation. It converts the intangible issues into tangible i.e., it quantify the subjective issues. According to Singh et al. (2013), GTA is a tool which is used to calculate the single numerical index of any issue. It helps to compare the different options available on the basis of the single numerical index. This approach gives a flexible and comprehensive model, which has the capability to consider the interdependencies between various measures and sub-measures affecting the FMS performance and helps in quantifying the influence of various measures and their sub-measures on FMS performance.

Because of inherent simplicity, Digraph and matrix approach has a diverse range of applications in various fields. It has been used for modeling and analyzing various kinds of systems and problems in numerous fields of science and technology (Attri et al., 2013). Different applications of GTA available in the literature are shown in Table 2.2.

Table 2.2: Brief review of GTA applications

S.No.	Authors	Applications
1	Mishra (2014)	Used the GTA methodology for the structural modeling and analysis of world-class maintenance system
2	Dev et al. (2014)	Used GTA for the analysis of combined cycle power plant efficiency
3	Nagar and Raj (2013)	Used the GTA approach for shifting to HFMS
4	Saha and Grover (2011)	Used the GTA approach for the evaluation of critical factors of website performance
5	Raj et al. (2010)	Used the GTA approach in evaluating the intensity of barriers in the implementation of FMSs
6	Faisal et al. (2007)	Used the GTA approach for the mitigation of risk in supply chain environment
7	Rao and Padmanabhan (2006)	Used the GTA approach for the selection of industrial robots

S.No.	Authors	Applications
8	Grover et al. (2006)	Used the GTA approach for analyzing human factors in TQM
9	Grover et al. (2004)	Used GTA for quantifying TQM environment
10	Venkatesh and Smith (2003)	Used the GTA approach to detect and resolve deadlocks in Flexible Manufacturing Cells
11	Rao and Gandhi (2002a)	Utilized the digraph and matrix approach in failure cause analysis of machine tools
12	Rao and Gandhi (2002b)	Demonstrated the graph theory to evaluate the machinability of work materials
13	Wani and Gandhi (1999)	Used this technique in the development of maintainability index of mechanical systems
14	Gandhi and Agrawal (1994)	Used the digraph approach to evaluate and analyze the system wears
15	Gandhi and Agrawal (1992)	Used digraph and matrix method for failure mode and effect analysis of mechanical and hydraulic system

The five categories of performance measures and their sub-measures, identified in this research work, have been utilized here to evaluate the index of performance (IOP) in FMSs. Hence:
Index of performance = $(\text{IOP})_{\text{FMS}} = f$ (Performance Measures).

This approach involves the digraph representation, matrix representation, and the permanent function representation. The digraph is the visual representation of the factors, sub-factors and their interdependencies in terms of nodes and edges. The matrix converts the digraph into mathematical form. The permanent function is a mathematical model that helps to determine index which is helpful for comparison.

2.7.3 Analytic Hierarchy Process (AHP)

AHP was first introduced by Saaty (1980) and has been applied in various fields of decision making. The simplicity and power of the AHP have led to its wide spread use across multiple domains in every part of the world. Its popularity has been increased in recent years in manufacturing and industrial applications. AHP has been proven as a powerful and useful technique for supporting managers in complicated and difficult decisions. AHP helps in evaluating various criteria to identify the best among the factors (Sundharam et al., 2013).

AHP is one of the multi-criteria decision making approaches that decomposes a complex problem into a hierarchical order (Abdi and Labib, 2003). According to Eraslan and Dagdeviren (2010), “A hierarchy is an efficient way to organize a complex system, as it is efficient structurally when representing the system and when controlling and passing information down the system.” AHP is a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales (Saaty, 2008). The degree of consistency of the judgments is computed in the AHP analysis (Wabalickis, 1987). Numerous papers have been published regarding mathematical aspects and applications of AHP to various situations (Saaty and Vargas, 1984; Saaty, 1986; Datta et al., 1992). AHP technique has been utilized in various decision-making problems associated with production, performance, location selection, flexibility, HFMS, advanced manufacturing system (AMS), investments, etc. Different applications of AHP available in the literature are shown in Table 2.3.

Table 2.3: Brief review of AHP applications

S.No.	**Authors**	**Applications**
1	Gothwal and Saha (2015)	Used AHP technique for the plant location selection for a manufacturing industry
2	Jain and Raj (2013)	Used AHP technique for the evaluation of flexibility in FMS
3	Attaran and Celik (2013)	Used AHP for green building market research
4	Nagar and Raj (2012)	Used AHP technique for the selection of HFMS: an Indian perspective
5	Abu-Sarhan (2011)	Used AHP approach in evaluation and selection of an information system re-engineering projects.
6	Eraslan and Dagdeviren (2010)	Utilized AHP approach for the performance measurement in FMSs
7	Raj et al. (2008b)	Utilized AHP approach for the selection of Advanced Manufacturing System

S.No.	Authors	Applications
8	Buyukozkan et al. (2004)	Used AHP for determining the importance weights for the design requirements in the house of quality
9	Vaidya and Kumar (2006)	Discussed the applications of AHP
10	Bozdag et al. (2003)	Utilized AHP approach for the selection of CIM systems
11	Xiaohua and Zhenmin (2002)	Used AHP for Advanced Manufacturing System
12	Kuo et al. (2002)	Utilized AHP approach for the selection of convenience store location
13	Badri (1999)	Used AHP for analyzing the global facility location-allocation problem
14	Triantaphyllou and Mann (1995)	Used AHP technique for decision making in engineering applications: Some challenges
15	Suresh and Kaparthi (1992)	Utilized AHP approach for analyzing the flexible automation investments

2.7.4 Simple Additive Weighting (SAW) Method

SAW method is probably the best known and most widely used MADM method (Anupama et al., 2015). SAW which is also known as weighted linear combination or scoring methods is a simple MADM technique (Afshari et al., 2010). Adriyendi (2015) stated that the basic logic of the SAW method is to obtain a weighted sum of performance ratings of each alternative over all attributes. Churchman and Ackoff (1954) were the first one to use the SAW method for portfolio selection problem. Ray et al. (2015) used SAW approach to determine the best location in their research. Zavadskas et al. (2010) used this approach for selecting the contractor for construction work. SAW approach was used for the personnel selection problem by Afshari et al. (2010). Chou et al. (2008) also used this method for selecting the facility location with objective/subjective attributes. The steps involved in computing the overall score of the alternatives by SAW method are mentioned below (Rao, 2007):

Step 1: In this step objective of the problem is determined, and the relevant evaluation performance measures and sub-measures are identified.

Step 2: By using AHP technique, weights of different measures and sub-measures are calculated. The steps are explained below:

- Construct a pairwise comparison matrix by using a scale of relative importance. The judgments are entered using the fundamental scale of the AHP (Saaty, 1980, 2000). A measure compared with itself is always assigned the value 1, so the main diagonal entries of the pairwise comparison matrix are all 1. The numbers 3, 5, 7 and 9 correspond to the verbal judgments 'moderate importance ', ' strong importance ', ' very strong importance ' and ' absolute importance' (with 2, 4, 6, and 8 for compromise between these values).
- Determine the maximum Eigen value λ_{max}, consistency index CI = (λ_{max} - M) / (M -1). The smaller the value of CI, the smaller is the difference from the consistency. Here, M is number of measures/sub-measures.
- Obtain the random index (RI) for the number of measures used in decision making. The value of RI varies depending upon the order of matrix.
- Calculate the consistency ratio CR = CI/RI. Usually, a CR of 0.1 or less is considered as acceptable, and it reflects that the judgment made has a good consistency.
- Global weights are used to compute the normalized weights of the sub-measures. It is determined by multiplying the priority vectors of each measure with the priority vectors of the sub-measures that come under the corresponding measure.

Step 3: Convert qualitative sub-measures to their corresponding fuzzy number and then convert the fuzzy number to their corresponding crisp values.

Step 4: Evaluate each measure P_i, by the following formula

$$P_i = \sum_{j=1}^{M} \left(w_j (m_{ij}) \right)$$

where w_j represents the global weights of sub-measures, m_{ij} represents the crisp value assigned to the sub-measures according to their importance within the corresponding measure and P_i is the overall or composite score of the measures. The measures with the highest value are considered as the first preference.

2.7.5 Weighted Product Method (WPM)

WPM is a popular multi-criteria decision making (MCDM) method. Atmojo (2014) stated that this method is more efficient than other methods in problem-solving of MCDM. The reason is that the time needed in the calculation is less as compared to the other methods. This method stood by simple calculation and easy to apply in cases having high subjectivity elements, effective to optimize decision problems. According to Anupama et al. (2015), WPM is another scoring method where the weighted product of the criterion is used to select the best alternative. The overall or composite performance score of measures is determined as

$$P_i = \prod_{j=1}^{M} [(m_{ij})]^{w_j}$$

The crisp values are computed in the similar way as explained in step 3 of SAW method. Each value of measure with respect to sub-measures, i.e., m_{ij} is raised to the power of the relative global weight of the corresponding sub-measure. The measure with the highest P_i value is considered as the first preference.

2.7.6 Analytic Network Process (ANP)

ANP was first introduced by Saaty (1996). He suggested the use of AHP to solve the problem of independence among alternatives and the use of ANP to solve the problem of dependence among alternatives. In literature, ANP has been widely used in solving many complicated decision-making problems. Meade and Sarkis (1999) used ANP to evaluate logistic strategies and to improve production speed, also discussed the organizational project alternatives for the agile manufacturing process. According to Katayama and Bennett (1999), Christopher (2000), Power et al. (2001), Prater et al. (2001), Stratton and Warburton (2003), Agarwal and Shankar (2005), Dagdeviren and Yuksel (2007), Lee et al. (2010), Chand et al. (2013) and Chand et al. (2015) various steps of ANP are:

Step 1: Define the objective and determine measures, sub-measures and the alternatives.

Step 2: Assuming no dependence among the measures, find out importance degrees of the measures. The judgments are entered using the fundamental scale of the AHP (Saaty, 1980, 2000).

Step 3: Determine the inner dependence matrix of each measure with respect to the other measure by using the schematic representation of inner dependence among the measures.

Step 4: Determine the interdependent priorities of the measures.

Step 5: Determine the priority vectors of the sub-measures.

Step 6: Determine the global importance degrees/ global weights of the sub-measures.

Step 7: Determine the importance degrees of the alternatives with respect to each sub-measure.

Step 8: Determine the overall priorities of the alternative reflecting the interrelationships within the measures.

Different applications of ANP available in the literature are shown in Table 2.4.

Table 2.4: Brief review of ANP applications

S.No.	Authors	Applications
1	Gaikwad et al. (2015)	Used ANP technique to recommend an ice cream to a diabetic patient
2	Neumuller et al. (2015)	Used this technique for integrating three-dimensional sustainability in distribution center selection
3	Chand et al. (2013)	Used ANP technique to analyze the risks in traditional, agile and lean supply chain.
4	Goyal and Grover (2013)	Used ANP for manufacturing system’s effectiveness measurement
5	Chen and Wu (2011)	Used this technique in logistics service provider selection – A case study of the industry investing in Southeast Asia
6	Anand et al. (2011)	Used ANP for the selection of MHSs in the design of FMS
7	Alptekin (2010)	Used this technique to predict the market share in white goods sectors
8	Saaty (2009)	For real application of ANP in an entertainment business
9	Khan and Faisal (2008)	Used ANP for analyzing the municipal solid waste disposal options

S.No.	Authors	Applications
10	Jharkharia and Shankar (2007)	For the selection of the logistics service provider
11	Bayazit (2006)	Used ANP for the vendor selection problem
12	Ravi et al. (2005)	Used the approach for the alternatives in reverse logistics for end-of-life computers
13	Niemira and Saaty (2004)	Used ANP in financial crisis forecasting
14	Mikhailov and Singh (2003)	Used ANP for the development process of a decision support system
15	Sarkis (2002)	Used ANP for supplier selection
16	Lee and Kim (2001)	Used the ANP approach in the interdependent information system project selection process
17	Meade and Sarkis (1999)	Used ANP to evaluate logistic strategies and to improve production speed

2.7.7 0-1 Linear Integer Programming

An integer programming is a mathematical optimization technique in which some or all of the variables are constrained to be integers. Zero-one linear integer programming involves problems in which the all the variables are restricted to be either 0 or 1. Many authors (Alam et al., 2015; Soolaki, 2013, Abbas et al., 2012; Banerjee and Barai, 2007; Guzman et al., 1997; Gaskin and Tanchoco, 1987; Goetz and Egbelu, 1990) used this mathematical programming in their research work for optimization. General formulation of the flow path design problem can be stated based on the following definitions of the decision variables and parameter values:

1) Decision Variables: A_{ij} represents the arc from node i to node j. If A_{ij} comes out to be 1 after solving the layout problem, which means it is included in the final path layout and if it comes out to be 0 then it is not included in the final path layout.

$$A_{ij} \begin{cases} 1 \text{ if the arc from node } i \text{ to node } j \text{ is} \\ \quad \text{included in the final layout} \\ 0 \text{ otherwise (i.e. if not included in the final layout)} \end{cases} \quad \text{…… …(1)}$$

2) Parameters: These parameters simply state the meaning of different symbols used in solving the problem as shown below:

   $d_{m,n,p}$ = Distance from node m to node n using path p
   $f_{m,n}$ = Flow intensity from node m to node n
   n_p = Total number of arcs in the path p

3) Objective function: Here the objective is to find the unidirectional flow path which, when the shortest routes are taken, will result in total loaded travel distance being minimized. So, keeping the objective in mind, objective function is written as,

Minimize

$$\mathrm{T} = \sum_m \sum_n f_{m,n} \sum_p [\, d_{m,n,p} A_{m,q} A_{r,n}]$$

$$q, r \in p; \forall f \qquad \ldots\ldots\ldots\ldots\ldots\ldots \ (2)$$

where,

$f_{m,n}$ is the flow intensity from node m to node n
$d_{m,n,p}$ is the distance from node m to node n using path p
$A_{m,q}$ is the arc from node m to node q
$A_{r,n}$ is the arc from node r to node n

Linearization of non-linear product terms:

The objective function presented in Equation 2 contains some product terms of the form $A_{m,q}A_{r,n}$. In the general model, having multiple load pick-up/delivery station, the product terms of two and more binary variables will be encountered. A function of the form

$$f = \ldots\ldots + b_m A_e A_f A_g + b_n A_k A_l + \ldots\ldots\ldots \qquad (3)$$

where A_i=0 or 1 and b_m is a constant, can be easily linearized through the use of the additional variable and constraints. Thus, the nonlinear function *f* above after linearization can be written with the function and constraints as,

$$f = \ldots\ldots + b_m A_{e,f,g} + b_n A_{k,l} + \ldots\ldots\ldots \qquad (4)$$

Subject to

$$A_e + A_f + A_g - A_{e,f,g} \leq 2 \qquad (5)$$

$$A_k + A_l - A_{k,l} \leq 1 \qquad (6)$$

$$-A_e - A_f - A_g + 3A_{e,f,g} \leq 0 \quad (7)$$

$$-A_k - A_l + 2A_{k,l} \leq 0 \quad (8)$$

$$A_e, A_f, A_g, A_{e,f,g}, A_k, A_l, A_{k,l} = 0 \text{ or } 1 \quad (9)$$

Using this form of conversion, the objective function becomes,

Minimize

$$T = \sum_m \sum_n f_{m,n} \sum_p [\, d_{m,n,p} A_{m,q,r,n}] \quad (10)$$

Subject to

$$\left.\begin{array}{l} A_{m,q} + A_{r,n} - A_{m,q,r,n} \leq 1 \\ -A_{m,q} - A_{r,n} + 2A_{m,q,r,n} \leq 0 \\ A_{m,q}, A_{r,n}, A_{m,q,r,n} = 0 \text{ or } 1 \end{array}\right\} \forall f_{m,n}, \forall p$$

4) Constraints:

a) Unidirectionality Constraints: The layout considered in the present problem is unidirectional i.e., the AGV is restricted to travel in only one direction along a given segment of the flow path. Therefore, to ensure the unidirectionality, this constraint is given:

$$A_{ij} + A_{ji} = 1$$

b) Constraints to ensure at least one input arc to each node: Each node must have at least one incoming arc i.e., each node is reachable. To ensure this, the following constraint is added

$$\sum_{\forall i} A_{i,j} \geq 1$$

$\forall j$; j is adjacent to i

c) Constraints to ensure at least one output arc to each node: Each node must have at least one outgoing arc i.e., each node is reachable. To ensure this, the following constraint is added

$$\sum_{\forall j} A_{i,j} \geq 1$$

$\forall i$; i is adjacent to j

d) Ensure shortest path is taken:

$$(n_p\text{-}2)A_{m,q} + (n_p\text{-}2)A_{r,n} - \sum_{\forall i,j \neq m,n} A_{i,j} \leq (n_p - 2) \qquad \text{in the path p}$$

e) This constraint is required whenever there is an undetermined arc in the shortest path. In those paths where there are no undetermined arcs, this constraint is optional. The above constraint can also be written as:

$(n_p$-2)(first arc) + $(n_p$-2)(last arc) – (sum of intermediate arcs) $\leq (n_p$-2)

where,

n_p is the total number of arcs in the path p.

f) An optimal constraint to force flow balance at four way node is given by

$$\sum_j A_{i,j} \geq 2$$

j is a four way node $\forall$ i ; adjacent to j

In the case of four way node, there will be more than one incoming and/or outgoing arcs. To ensure this, the above constraint is given that there should be at least 2 outgoing arcs.

g) Prevent a group of nodes from becoming sink nodes: Also the same group of nodes needs to be reachable.

2.8 CONCLUSION

In this chapter, FMS has been classified and a broad view on FMS issues has been presented. Various issues related to design and development of FMS, i.e., planning issues, design issues, scheduling and control issues, operational issues, flexibility issues, MHS issues, performance measurement issues, fixture and pallets issues and justification of FMS have been discussed. FMS performance is directly influenced by the type of MHS to be used. Thus, when designing an FMS, decisions should be made based on the MHS being used. Although FMS can offer a number of potential benefits over conventional manufacturing systems, its implementation demands a high investment in the capital but at high risk. From the literature, it is found that there are various factors which could affect the design and development of FMS, so it is very necessary to identify and analyze these factors. Various factors/measures affecting the FMS in various ways have been identified and analyzed, for the successful implementation of FMS. Various methodologies used in this research work i.e., W-ISM, ANP, AHP, SAW, WPM, GTA and 0-1 linear integer programming have been discussed.

CHAPTER III

QUESTIONNAIRE ADMINISTRATION AND DESCRIPTIVE STATISTICS

3.1 INTRODUCTION

In this chapter, a questionnaire based survey approach and results have been presented with the objective to examine some issues related to design and development of an FMS in Indian industries. Key observations from the survey have been discussed and analyzed. Some other aspects such as questionnaire development, its administration in the industry as well as in academics have been discussed in this chapter.

3.2 QUESTIONNAIRE DEVELOPMENT

The questionnaire-based survey was undertaken to address various issues related to design and implementation of FMSs in Indian industries. The questionnaire was designed and developed keeping in view the literature review and discussion with the experts both from industry and academicians' in this domain. As the response rate of such survey are not encouraging, and respondents are generally reluctant to spare time to respond to such questionnaire, therefore the questionnaire was designed in keeping such views in mind so that the minimum time and efforts are needed in filling the questionnaire. The questionnaire was designed on five-point (1 to 5) Linkert's scale. On this scale, 1 corresponds to very low importance, 2 correspond to low importance, 3 correspond to moderate importance, 4 correspond to high importance, and 5 correspond to very high importance. The questionnaire was divided into two sections. Section 1 dealt with the organization profile and Section 2 dealt with the different issues related to FMS i.e., various factors affecting the machine, product and routing flexibilities, factors affecting the design and implementation of AGVs, factors affecting the performance measurement and factors affecting the design and development of flexible fixture and pallets.

3.3 QUESTIONNAIRE ADMINISTRATION

The self-contact, e-mail, online survey mode, telephonic mode and face to face filling up methods were used for the administration of the questionnaire. The survey was conducted in

Indian manufacturing industries. The questionnaire was administered to chief-executives/managing directors/general managers/works managers/senior executives from Indian manufacturing industries. In total, questionnaires were sent to 550 Indian industries.

3.4 QUESTIONNAIRE SURVEY RESPONSE AND RESPONDENTS PROFILE

Out of 550 questionnaires, 103 completed questionnaires were received. This gives a response rate of 18.7 %, which is not very low for such surveys (Malhotra and Grover, 1998). On the basis of the responses of the survey, the company data of 103 respondents is presented in Table 3.1.

Table 3.1: The data of the responding companies

S.No.	Description of data	Range	Percentage of firms
1	Number of employees	Less than 100	0
		101 to 500	47
		501 to 1000	17
		1001 to 2000	17
		More than 2000	22
2	Turnover (Crore of Rs.)	Less than 10	0
		10 to 50	11
		50 to 100	17
		100 to 500	27
		500 to 1000	19
		More than 1000	28
3	Variety of models	1-5	4
		6-10	14
		11-20	31
		More than 20	53

S.No.	Description of data	Range	Percentage of firms
4	% of components manufactured	Less than 25	0
		25-50	4
		50-75	21
		75-90	41
		90-100	36
5	Current productivity	Less than 10	2
		10-25	2
		25-50	10
		50-100	63
		More than 100	23

3.5 OBSERVATIONS FROM THE SURVEY

The various important issues related to design and development of FMS were emphasized in this survey such as various factors affecting the machine, product and routing flexibilities, factors affecting the design and implementation of AGVs, factors affecting in the performance measurement and factors affecting the design and development of flexible fixture and pallets. The survey result has been presented in the following sections:

3.5.1 Related to Machine Flexibility

Among the factors affecting the machine flexibility, the most important type of factor indicated by the respondents is setup or changeover time with a mean score of 4.35. If the amount of time spent in setting up the fixture, calculating tool offsets and carrying out all the essential jobs in switching from one operation to the another operation, i.e., setup time is reduced then the machine downtime will reduce and the machine will be available for performing more production activities. In FMS, machines are quite versatile with automatic tool interchanging capability that reduces the set-up time which in turn helps to increase the overall output and machine flexibility. Similarly, other factors with their mean score and rank as indicated by the respondents are presented in Table 3.2.

Table 3.2: Factors affecting machine flexibility with their mean score and rank

S.No.	Factors affecting machine flexibility	Mean Score	Rank
1	Types of machine	4.27	4
2	Maximum number of tools available	4.26	5
3	Maximum number of operation available	4.19	7
4	Tool magazine or tool turret capacity	4.33	2
5	Tool changing time of the machine	4.17	8
6	Type of operations to be done on machine	4.11	9
7	Variety of parts to be handled by the machine	4.2	6
8	Skills and versatility of workers in the system	4.31	3
9	Setup or changeover time	4.35	1

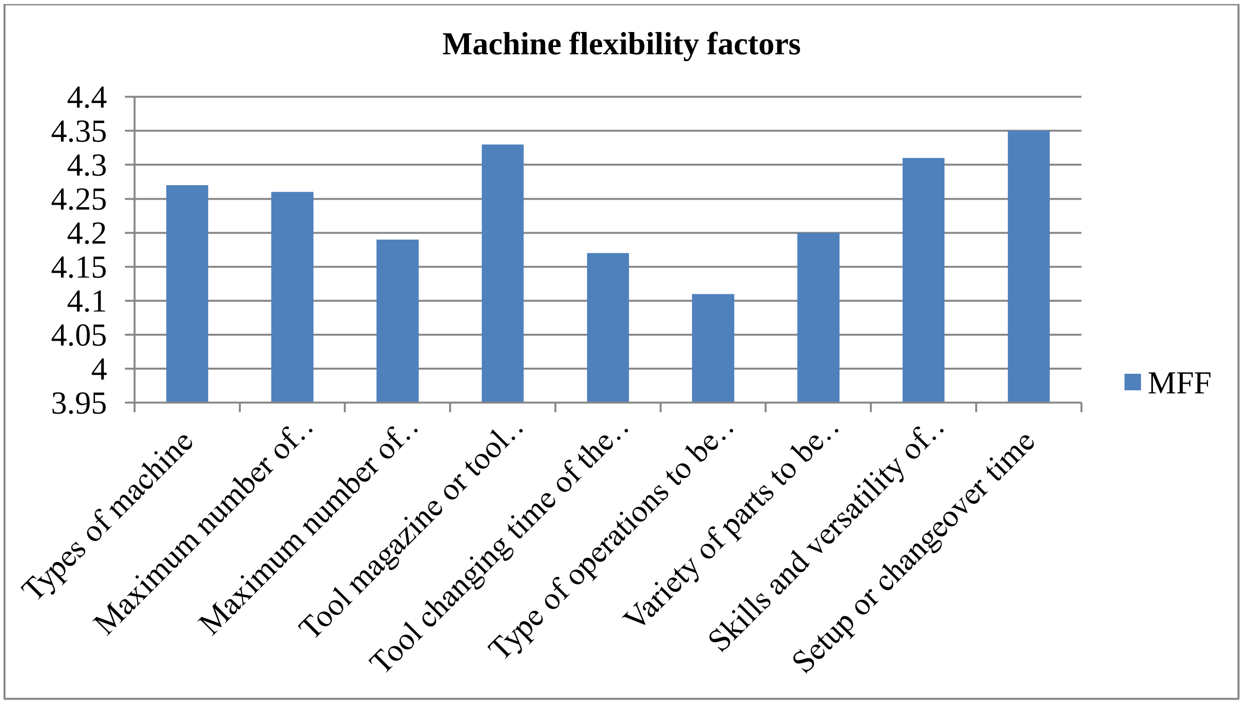


Figure 3.1: Factors affecting machine flexibility

3.5.2 Related to Routing Flexibility

Among the factors affecting the routing flexibility, the most important type of factor indicated by the respondents is the availability of technical know-how with a mean score of 4.32. If the multi-skilled workers with the knowledge of better operational techniques are available then in the case of machine breakdown or other technical problems, the major problems during operations are solved because they can understand the problems in less time. They can find out which one is the best route to perform a particular operation. Similarly, other factors with their mean score and rank as indicated by the respondents are presented in Table 3.3.

Table 3.3: Factors affecting routing flexibility with their mean score and rank

S.No.	Factors affecting routing flexibility	Mean Score	Rank
1	Number of machines available in the system	4.26	2
2	Maximum number of routes available	4.12	8
3	Similarity of workstations	4.13	7
4	Common tooling available	4.19	4
6	Space availability	4.2	3
7	Availability of technical know how	4.32	1
8	Flexibility of MHS	4.15	6
9	Similarities of parts in the system	4.18	5

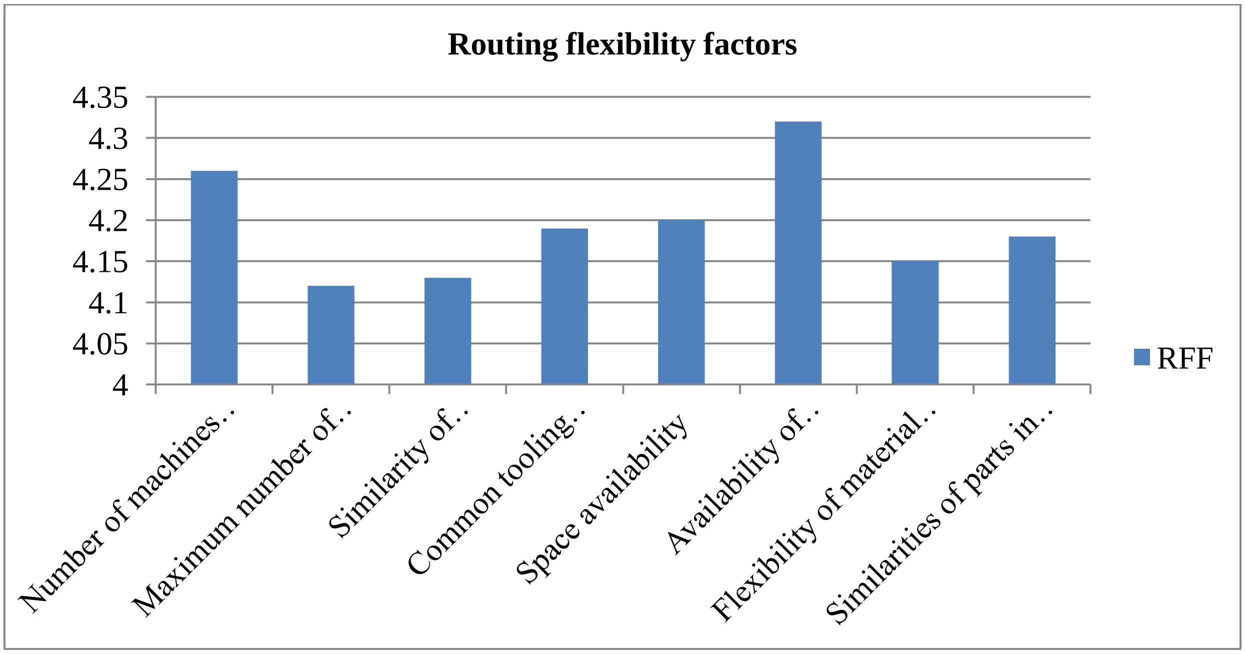


Figure 3.2: Factors affecting routing flexibility

3.5.3 Related to Product Flexibility

Among the factors affecting the product flexibility, the most important type of factor indicated by the respondents is machine flexibility with a mean score of 4.33. If the flexibility of a machine is high, the machine can handle a larger range of operations and part styles. If a production system is capable of handling multiple varieties of part types then the product flexibility of that system will be more. Similarly, other factors with their mean score and rank as indicated by the respondents are presented in Table 3.4.

Table 3.4: Factors affecting product flexibility with their mean score and rank

S.No.	Factors affecting product flexibility	Mean Score	Rank
1	Design changes required in the product	4.17	3
2	Variety of products	4.18	2
3	Offline part programming preparation facility	4.11	5
4	Number of existing part families matching the new product design	4.13	4
5	Machine flexibility	4.33	1

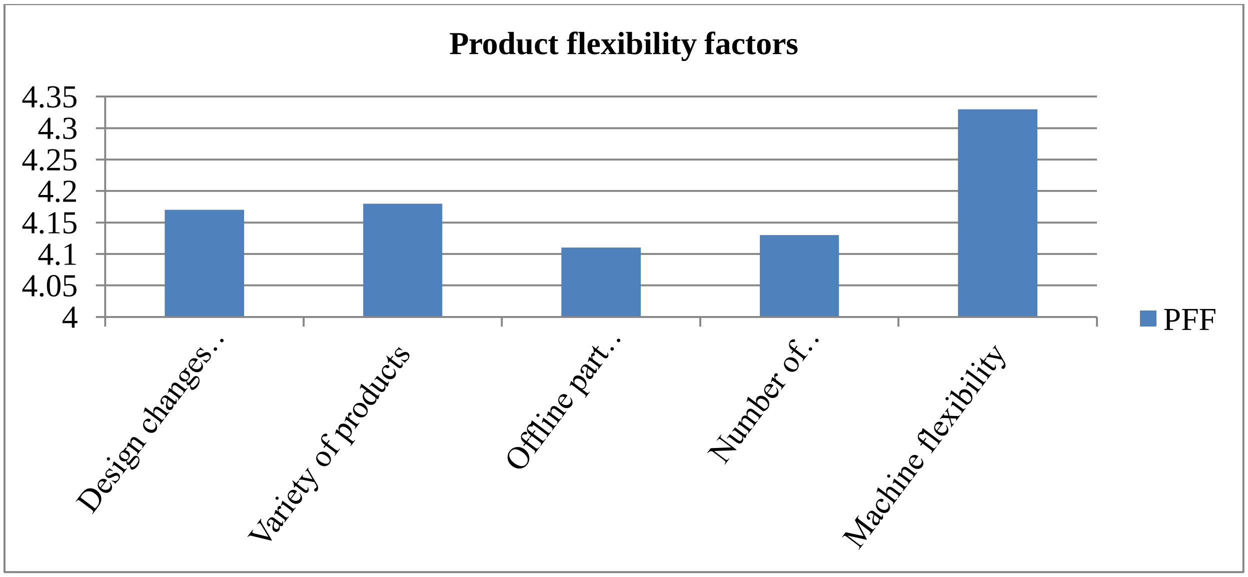


Figure 3.3: Factors affecting product flexibility

3.5.4 Related to Design and Implementation of AGVs

Among the factors affecting the design and development of AGVs, the most important type of factor indicated by the respondents is buffer capacity of each vehicle with a mean score of 4.35. Buffer basically provides the temporary storage for the in-process inventory which remains on the MHS before being processed on a particular workstation on which another operation is going on. Buffer capacity of each vehicle is a very important factor to be considered during the design and development of AGVs for reducing the waiting time and for the effective machine tool utilization. Similarly, other factors with their mean score and rank as indicated by the respondents are presented in Table 3.5.

Table 3.5: Factors affecting the design and development of AGVs with their mean score and rank

S.No.	Factors	Mean score	Rank
1	AGVs path layout	4.14	10
2	Volume of production	4.27	2
3	Traffic management technique	4.17	7
4	Layouts of AGV tracks in the industry	4.17	7
5	Economic condition of the industry	4.11	13
6	Organization culture	4.13	11
7	Maintenance requirements of AGV	4.18	6
8	Information management system	4.19	5
9	Process sequence of the manufacturing system	4.17	7
10	Positioning of idle vehicles	3.99	14
11	Communication system	4.12	12
12	Facility layout	4.23	4
13	Battery management	4.15	9
14	Procurement of AGV's	4.16	8
15	Failure management	4.27	2
16	Management of control zone	4.24	3

S.No.	Factors	Mean score	Rank
17	Speed of AGVs	4.18	6
18	Proper training	4.13	11
19	Buffer capacity of each vehicle	4.35	1

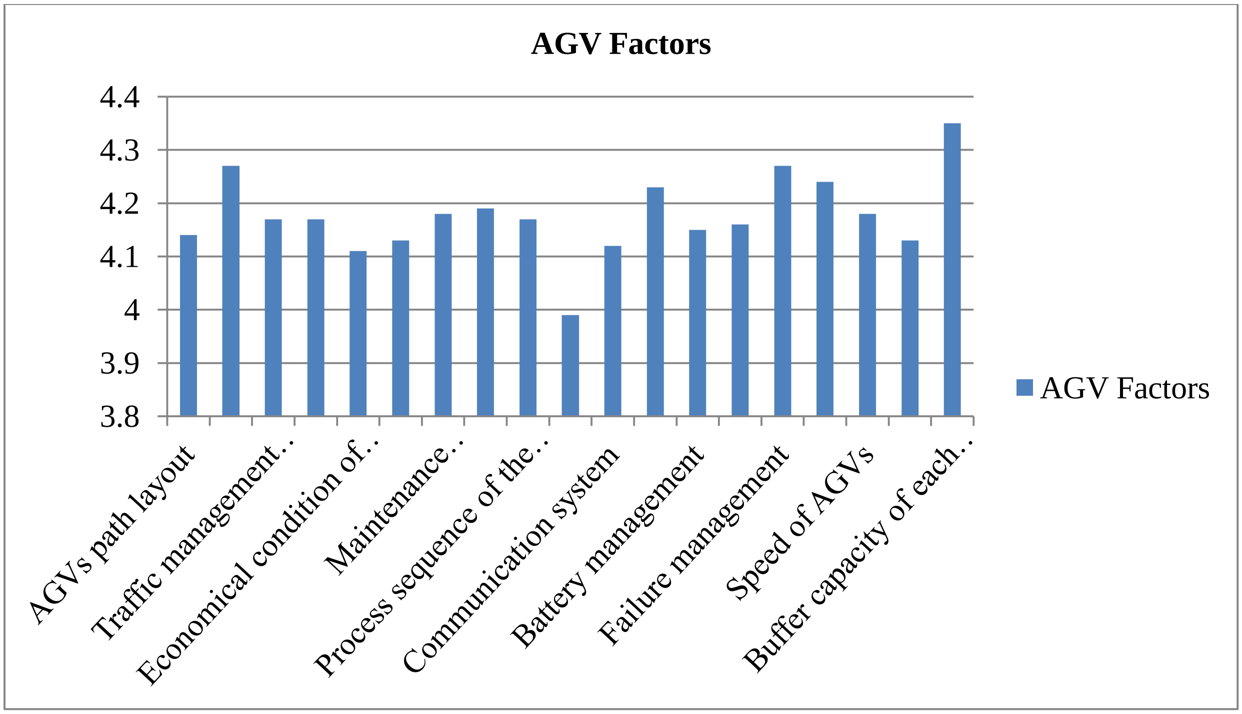


Figure 3.4 Factors affecting the design and development of AGVs

3.5.5 Performance Measurement Related to Finance

Among the sub-measures/factors affecting the performance related to finance of the FMS, the most important sub-measure indicated by the respondents is return on investment (ROI) with a mean score of 4.28. Due to the high cost involved with an FMS, it is vital to handle them efficiently in order to achieve projected goals with minimal investment risks. If ROI is high, then profit margins will be lesser, and it will be encouraging aspect for the management. Similarly, other sub-measures with their mean score and rank as indicated by the respondents are presented in Table 3.6.

Table 3.6: Sub-measures affecting the performance related to finance with their mean score and rank

S.No.	Sub-measures related to finance	Mean Score	Rank
1	Return on investment (ROI)	4.28	1
2	High-profit margins	4.27	2
3	Costs of sold goods	4.23	3
4	Growth in market share	4.2	4
5	Value-aided production	4.17	5
6	Reduction of warranty costs	4.17	5

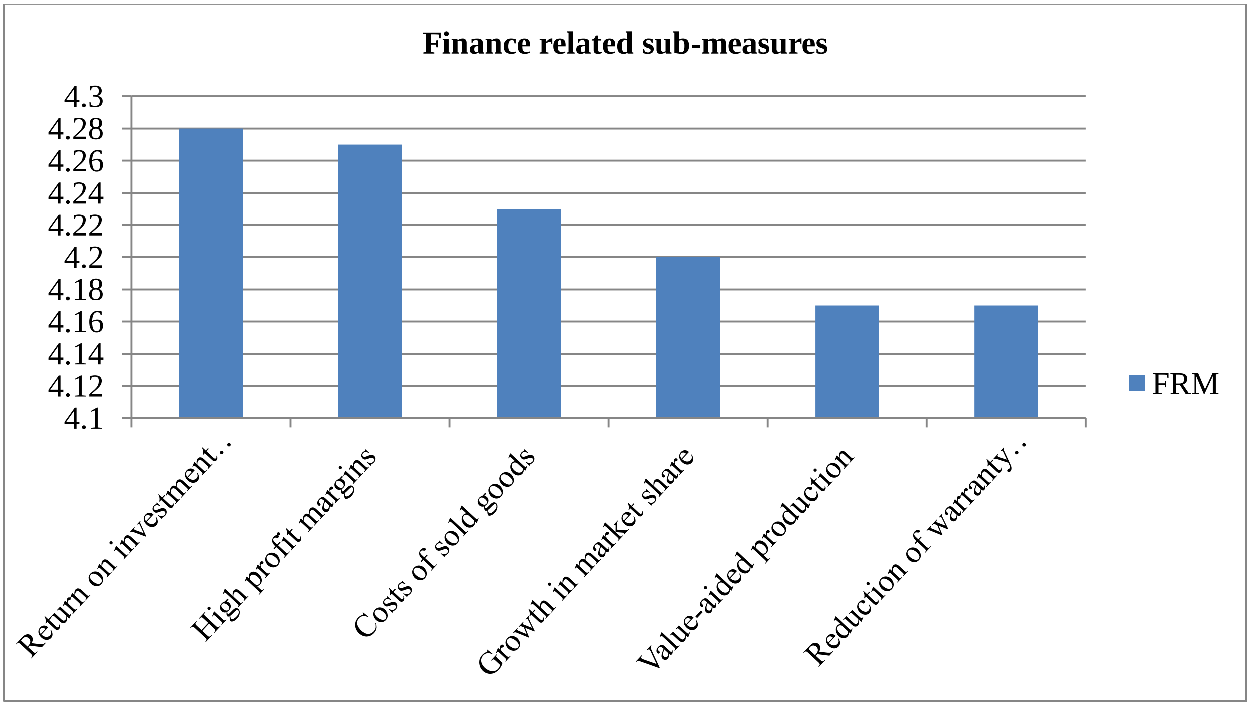


Figure 3.5: Sub-measures related to Finance

3.5.6 Performance Measurement Related to Customers

Among the sub-measures/factors affecting the performance related to customers, the most important type of measure indicated by the respondents is the life of the product with a mean score of 4.3. If the life of the product is good, the company will get a good response from the customers. With the good life of the product, the customers will be satisfied with the product and sales revenue will automatically increase. Similarly, other sub-measures with their mean score and rank as indicated by the respondents are presented in Table 3.7.

Table 3.7: Sub-measures affecting the performance related to customers with their mean score and rank

S.No.	Sub-measures related to customers	Mean Score	Rank
1	Life of product	4.3	1
2	Customer satisfaction	4.28	2
3	After delivery services	4.25	3
4	Maintenance cost	4.17	8
5	Cost of product	4.25	3
6	Improved product quality	4.23	5
7	Timely delivery	4.24	4
8	Improved flexibility	4.2	7
9	Perfect order fulfillment	4.21	6

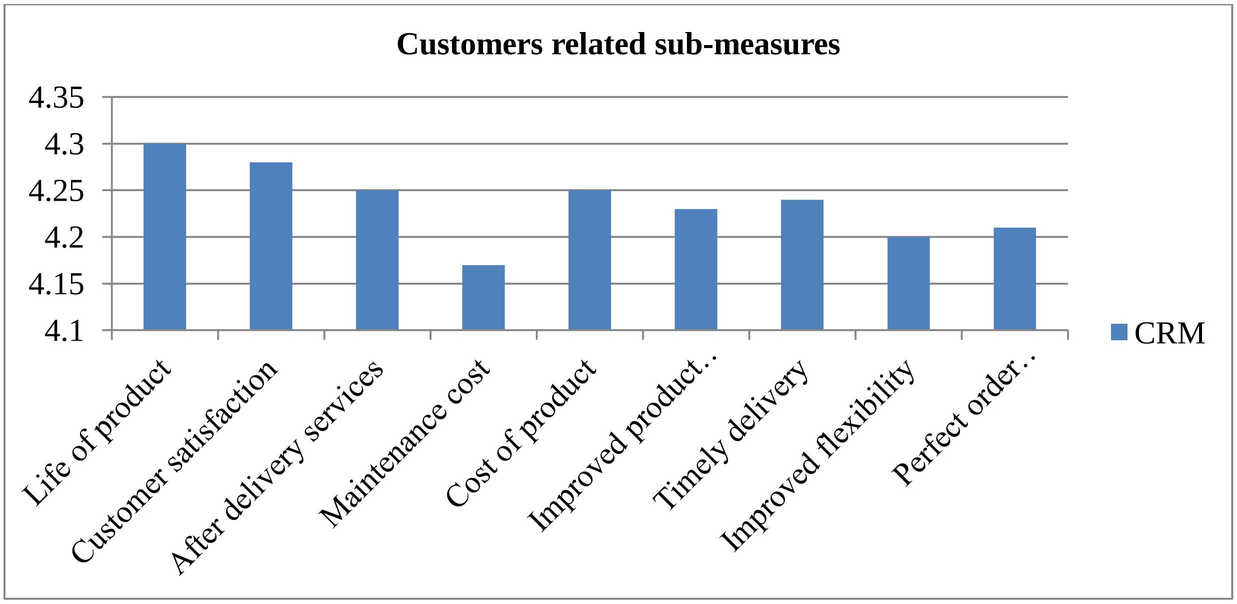


Figure 3.6: Sub-measures related to customers

3.5.7 Performance Measurement Related to Internal Business

Among the sub-measures/factors affecting the performance related to the internal business of the FMS, the most important type of measure indicated by the respondents is reduction in WIP and queues with a mean score of 4.3. Reduction in WIP and queues are critical performance sub-measures because if they are high, then they will create traffic jam due to that there will be congestion in the system and waiting time and throughput time will increase which results in poor performance. Similarly, other sub-measures with their mean score and rank as indicated by the respondents are presented in Table 3.8.

Table 3.8: Sub-measures affecting the performance related to internal business with their mean score and rank

S.No.	Sub-measures related to internal business	Mean Score	Rank
1	Reduction in WIP and queues	4.3	1
2	Assets utilization	4.23	4
3	Flexible environment	4.23	4
4	Throughput time	4.21	5
5	Reduced waste	4.13	8
6	Inventory turnover ratio	4.17	7
7	Time compression	4.2	6
8	On time delivery	4.26	3
9	Better integration	4.28	2

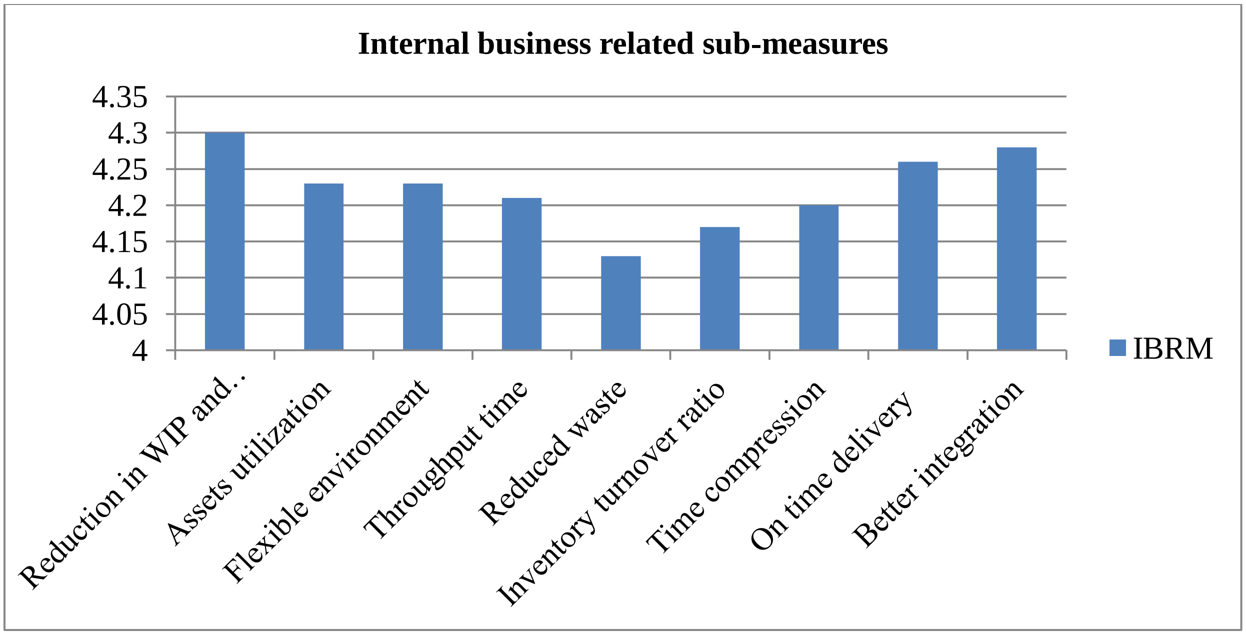


Figure 3.7: Sub-measures related to internal business

3.5.8 Performance Measurement Related to Innovation and Knowledge

Among the sub-measures/factors affecting the performance related to innovation and knowledge of the FMS, the most important type of measure indicated by the respondents is awareness of challenges ahead with a mean score of 4.36. Awareness of challenges ahead in the business activities of the enterprises is considered necessary to provide a clear vision of what to do, how to do and at what time to do otherwise decision makers will not be able to take appropriate and proper decisions at the right time which results in the poor utilization of resources and poor performance. Similarly, other sub-measures with their mean score and rank as indicated by the respondents are presented in Table 3.9.

Table 3.9: Sub-measures affecting the performance related to innovation and knowledge with their mean score and rank

S.No.	Sub-measures related to innovation and knowledge	Mean Score	Rank
1	Awareness of challenges ahead	4.36	1
2	Dynamic and proficient management	4.3	2

S.No.	Sub-measures related to innovation and knowledge	Mean Score	Rank
3	Product innovation	4.28	3
4	Process innovation	4.22	4
5	Accurate data and information system	4.22	4
6	Flexible production	4.17	5

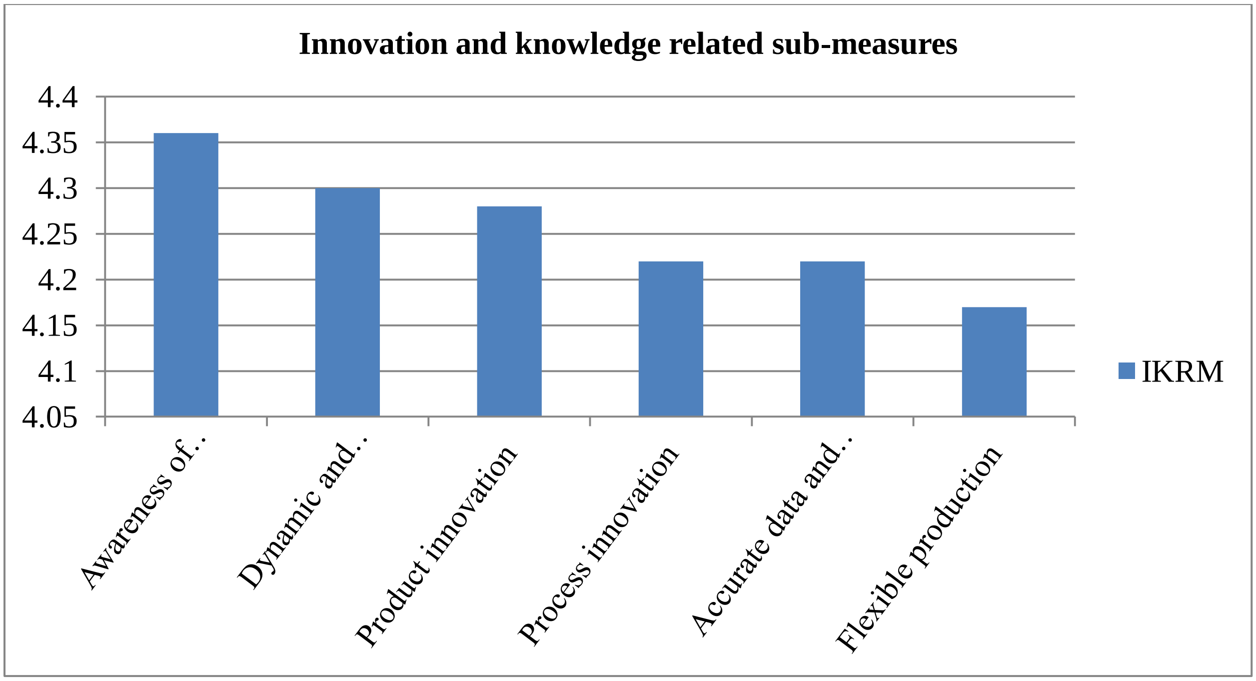


Figure 3.8: Sub-measures related to innovation and knowledge

3.5.9 Performance Measurement Related to Operational Measures

Among the sub-measures/factors affecting the performance related to operational measures of the FMS, the most important sub-measure indicated by the respondents is lead time with a mean score of 4.35. Lead time is a crucial part of managing a manufacturing business that involves waiting for supplies or products to arrive. Generally, lower the lead time, more flexible the company is, and it can respond to changes in trends at a faster rate. Customer satisfaction also increases with reduction in lead time because they get the product deliveries on time or before time, so overall performance of FMS increases. Similarly, other sub-measures with their mean score and rank as indicated by the respondents are presented in Table 3.10.

Table 3.10: Sub-measures affecting the performance related to operational measures with their mean score and rank

S.No.	Operational sub-measures	Mean Score	Rank
1	Processing time	4.34	2
2	Type and number of operations	4.33	3
3	Routing flexibility	4.28	6
4	Multi-functional machines	4.24	8
5	Number of parts produced	4.23	9
6	Lead time	4.35	1
7	Makespan	4.27	7
8	Flow time per item	4.17	10
9	Delay time at local buffers	4.3	5
10	Machine utilization	4.33	3
11	Shifts overtime	4.11	12
12	Setup time	4.27	7
13	Goods performance-measuring techniques	4.16	11
14	Skilled workers	4.32	4

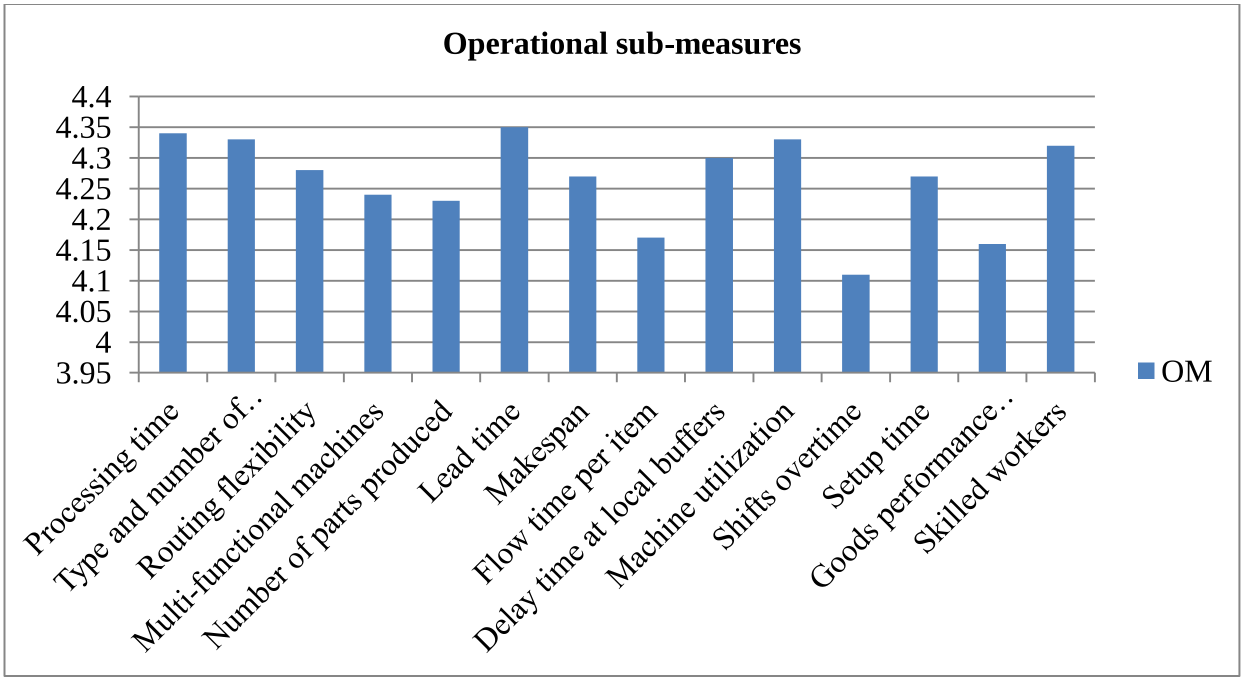


Figure 3.9: Operational sub-measures

3.5.10 Related to Design and Development of Flexible Fixture and Pallets

Among the factors affecting the design and development of flexible fixture and pallets, the most important type of factor indicated by the respondents is the flexibility of fixtures with a mean score of 4.28. The flexibility of fixture is important because custom-oriented dedicated fixtures do not provide flexibility to deal with workparts or assemblies of different shapes and sizes and they are also time-consuming and costly to build. Flexible fixture can handle a variety of workpart configurations, therefore, decreases the expenditure on redesigning of fixture if there are minor changes in the shape and size of the workpiece. Similarly, other factors with their mean score and rank as indicated by the respondents are presented in Table 3.11.

Table 3.11: Factors affecting the design and development of flexible fixture and pallets with their mean score and rank

S.No.	Factors	Mean score	Rank
1	Level of WIP allowed	4.1	10
2	Flexibility of fixtures	4.28	1

S.No.	Factors	Mean score	Rank
3	Clamping force required in the fixture	4.16	7
4	Cost-effectiveness of fixture	4.15	8
5	Fixture setup time	4.19	5
6	Workpiece deformation	4.13	9
7	Capacity of pallet	4.22	3
8	Swing diameter	4.19	5
9	Safety	4.15	8
10	Difference in the part style and size	4.17	6
11	Ease with which parts can be loaded or unloaded from the fixture	4.26	2
12	Clamping stability	4.26	2
13	Workpiece equilibrium	4.2	4
14	Static and Dynamic rigidity of workpiece	4.22	3
15	Processing stability	4.13	9
16	Fixture dexterity	4.2	4

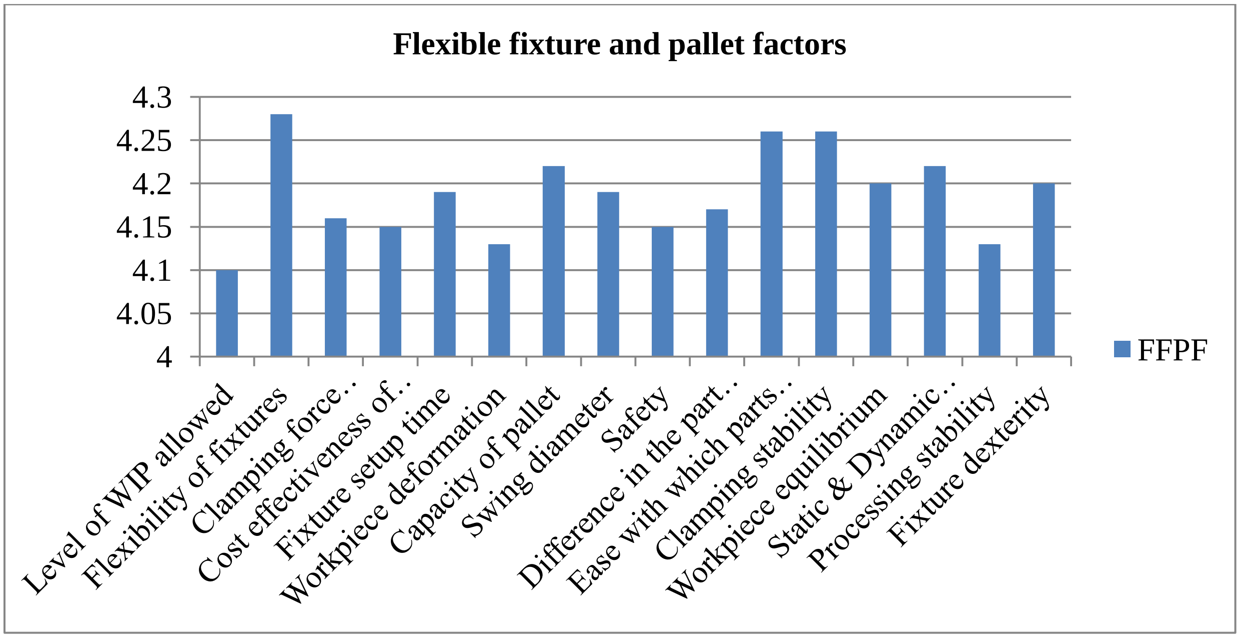


Figure 3.10: Factors related to flexible fixture and pallets

3.6 CONCLUSION

Different issues related to the design and development of FMS in Indian industries have been analyzed through the questionnaire based survey. The main objective of this survey was to determine the attitude of Indian industries towards the various issues related to the implementation of an FMS. From the survey, it is concluded that there are many factors which are forcing the industries to implement FMS in developing countries. This research empirically examines the response of Indian industries towards the adoption and implementation of FMS. Many industries have invested heavily in CNC machine tools which are considered as the pre-requisite for the implementation of FMS.

CHAPTER IV

ANALYSIS OF FACTORS AFFECTING THE FLEXIBILITY IN FMS

4.1 INTRODUCTION

In today's highly volatile and competitive market situations, the flexibility a production system is measured in terms of its adaptability and quickness in responding to unfavorable market changes/factors, capability in reducing the internal manufacturing cost of goods and services and ability in capturing good market share. The performance of a manufacturing industry is not solely dependent on the product price, equal importance has been given to other competitive factors such as flexibility, quality and delivery (Chan and Swarnkar, 2006). According to Ozbayrak and Bell (2003), in an attempt to improve their competitive edge, manufacturers have been moving to the advanced manufacturing technology like FMS. FMS consists of several computer-controlled machines interconnected by automated MHSs to provide high productivity and manufacturing flexibility (Singholi et al., 2012). Chen and Ho (2005) proposed that an FMS has the capability of producing various part styles simultaneously and provides flexible routing of workparts instead of processing parts in a straight line through machines. Though the flexibility of a production system can be enhanced through FMS but real-life flexibility is very hard to attain (Jain and Raj, 2015).

Several researchers have discussed alternative taxonomies for manufacturing flexibility (Raj et al., 2012; Singholi et al., 2012; Nayak and Ray, 2012; Browne et al., 1984; Swamidass, 1988). Operational measures of flexibility have been discussed by (Chung and Chen, 1989, 1990; Graves, 1988; Kumar, 1987; Soon and Park, 1987). Singholi et al. (2013) proposed that flexibility affects the overall performance of an FMS. In their research, they considered two types of flexibility: machine and routing flexibility to show their effect on the performance of FMS. According to Kumar and Sharma (2015), the unexpected events affects the overall performance of manufacturing system which can be handled by incorporating flexibility dimensions with respect to design, operation, and management of manufacturing system. Babu and Srinivasan (2010) also discussed the impact of volume, routing and product mix flexibilities on the performance of a job shop. Scheduling and manufacturing flexibility are among the manufacturing strategies considered by the researcher to improve the FMS performance.

Swamidass (1988) attributes the difficulties of understanding flexibility in his literature and observed that “the scope of flexibility related terms used by various authors overlap considerably, some flexibility terms are aggregate of other flexibility terms used, and identical flexibility related terms used by more than one author do not necessarily mean the same thing.” This view has been endorsed by Chung and Chen (1990) and Bernardo and Mohamed (1992). So, despite the extensive attention given by numerous researchers, theoretical and practical implication of real-time flexibility still remained poorly understood and utilized (Beskese et al., 2004). Within the scope of present research work, only three types of flexibilities: machine, routing and product flexibility are considered.

Though the flexibility of a production system can be enhanced through FMS, but this flexibility is highly influenced by some factors. Therefore, it is vital to analyze these factors and determine some key variables affecting the amount of flexibility in FMS. These factors, not only influence flexibility, also have an impact on each other. Based on the literature review, questionnaire-based survey and discussion with the experts both from industry and academia, 12 factors have been identified, and these factors are enlisted in Table 4.1. Factors’ ranking has been done based on the mean scores obtained from the results of the questionnaire-based survey. The methodology of an ISM has been applied for developing a model that establishes the interpretive relationship between these factors and a method of EI is used to analyze these factors. The interpretation of factors in terms of their driving and dependence powers has been examined.

The main objectives of this chapter are as follows:

- To identify and rank the factors affecting flexibility of FMS
- To evaluate the EI of these factors
- To establish relationship among these factors using ISM

Table 4.1: Factors affecting machine, routing and product flexibilities in FMS

S.No.	Factors affecting different flexibilities	Mean score	Rank	References/Sources
1	Setup or changeover time	4.35	1	De Groote (1988); Groover (2003)
2	Tool magazine or tool turret capacity	4.33	2	Groover (2003)
3	Skills and versatility of workers in the system	4.31	3	Piore and Sabel (1984); Groover (2003)
4	Type of machines	4.27	4	Groover (2003)
5	Variety of parts to be handled by the machine	4.2	5	Bayazit (2005); Groover (2003); Raj et al. (2012)
6	Space availability	4.2	6	Expert Opinion
7	Tool changing time of the machine	4.17	7	Browne et al. (1984)
8	Design changes required in the product	4.17	8	Primrose and Verter (1996); Sujono and Lashkari (2007)
9	Flexibility of material handling system	4.15	9	Groover (2003)
10	Maximum number of routes available	4.12	10	Groover (2003)
11	Type of operations to be done on the machine	4.11	11	Groover (2003)
12	Offline part programming preparation facility	4.11	12	Groover (2003)

4.2 W-ISM APPROACH FOR MODELING THE FACTORS OF FLEXIBILITY IN FMS

A W-ISM approach has been used for analyzing and developing the framework for the factors affecting the flexibility. The framework has been developed by utilizing ISM, and it has been further used to compute the EI of the factors. Flow chart for developing the ISM has been shown in Figure 4.1. The various steps involved in the development of ISM model, are discussed below:

Step 1: Establishing the Contextual Relationship between Factors

For analyzing the factors (12 in the present case) identified through the literature review and expert opinion, a contextual relationship of 'reaches to' type is chosen. Based on this, a contextual relationship among the factors is determined. For developing the contextual relationship among the factors interactions with some experts, both from industry and academia, have been done. The relationship between any two factors (i and j) and direction of that relation has been determined by keeping in mind the contextual relationship for each factor.

The symbols used to indicate the direction of the relation between any two factors (i and j) are:

- If factor i is related to factor j then, symbol V is used (i.e. if factor i reaches to factor j).
- If factor j is related to factor i then, symbol A is used (i.e. if factor j reaches to factor i).
- If factor i and factor j are related to each other then, symbol X is used (i.e. if factors i and j reach to each other).
- If factor i and factor j are not related to each other then, symbol O is used (i.e. if factors i and j are unrelated).

Step 2: Development of SSIM

On the basis of the contextual relationship among the factors, the SSIM has been developed. To obtain consensus, the SSIM was discussed with a group of experts. On the basis of their opinions, SSIM has been finalized and shown in Table 4.2. The four symbols used in developing SSIM are explained below:

- Symbol V is assigned to cell (2, 5) because factor 2 reaches to factor 5.
- Symbol A is assigned to cell (1, 4) because factor 4 reaches to factor 1.
- Symbol X is assigned to cell (6, 9) because factors 6 and 9 reach to each other.
- Symbol O is assigned to cell (7, 12) because factors 7 and 12 are unrelated.

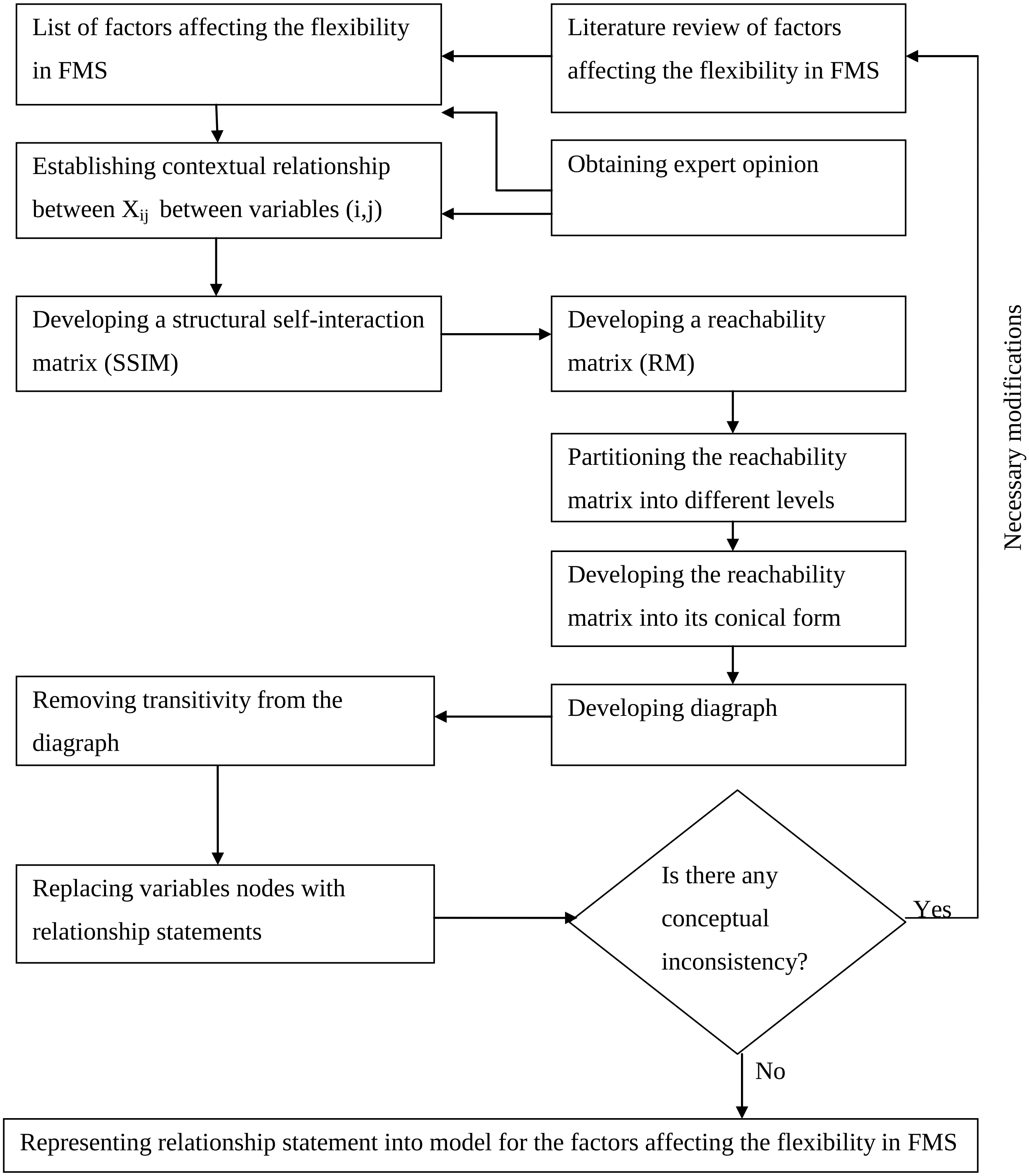


Figure 4.1: Flow chart for preparing ISM

Table 4.2: Structural Self – Interactive Matrix (SSIM)

Factors	12	11	10	9	8	7	6	5	4	3	2
1	A	A	O	O	A	O	O	O	A	A	O
2	O	V	O	O	O	O	O	V	A	O	
3	V	V	X	V	V	V	O	V	A		
4	O	V	V	V	V	V	V	V			
5	O	V	A	O	A	V	O				
6	V	O	A	X	A	O					
7	O	X	A	O	O						
8	O	V	A	O							
9	O	V	O								
10	O	V									
11	A										

Step 3: Development of RM

RM is obtained from SSIM. There are two type of RM: initial RM and final RM. The SSIM is converted into a binary matrix, called the initial RM by substituting V, A, X and O by 1 and 0 as shown in Table 4.3. The substitution of 1s and 0s has been done with the following rules:

- If the cell (i, j) is assigned with symbol V in the SSIM, then this cell (i, j) entry becomes 1, and the cell (j, i) entry becomes 0 in the initial RM.
- If the cell (i, j) is assigned with symbol A in the SSIM, then this cell (i, j) entry becomes 0, and the cell (j, i) entry becomes 1 in the initial RM.
- If the cell (i, j) is assigned with symbol X in the SSIM, then this cell (i, j) entry becomes 1, and the cell (j, i) entry also becomes 1 in the initial RM.

- If the cell (i, j) is assigned with symbol O in the SSIM, then this cell (i, j) entry becomes 0, and the cell (j, i) entry also becomes 0 in the initial RM.

For developing final RM, the concept of transitivity is incorporated so that some of the cells of the initial RM are filled by inference. The transitivity concept is used to fill the gap, if any, in the opinions collected during the development of SSIM. The final RM after incorporating the concept of transitivity is presented in Table 4.4. 1* entries are included to incorporate transitivity.

Table 4.3: Initial Reachability Matrix

Factors	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	1	0	0	0	0	0	1	0
3	1	0	1	0	1	0	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	0
5	0	0	0	0	1	0	1	0	0	0	1	0
6	0	0	0	0	0	1	0	0	1	0	0	1
7	0	0	0	0	0	0	1	0	0	0	1	0
8	1	0	0	0	1	1	0	1	0	0	1	0
9	0	0	0	0	0	1	0	0	1	0	1	0
10	0	0	0	1	1	1	1	1	0	1	1	0
11	1	0	0	0	0	0	1	0	0	0	1	0
12	1	0	0	0	0	0	0	0	0	0	1	1

Table 4.4: Final Reachability Matrix

Factors	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0	0	0	0	0	0	0	0	0	0	0
2	1*	1	0	0	1	0	1*	0	0	0	1	0
3	1	0	1	1*	1	1*	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1*
5	1*	0	0	0	1	0	1	0	0	0	1	0
6	1*	0	0	0	0	1	0	0	1	0	1*	1
7	1*	0	0	0	0	0	1	0	0	0	1	0
8	1	0	0	0	1	1	1*	1	1*	0	1	0
9	1*	0	0	0	0	1	1*	0	1	0	1	1*
10	0	0	0	1	1	1	1	1	1*	1	1	1*
11	1	0	0	0	0	0	1	0	0	0	1	0
12	1	0	0	0	0	0	0	0	0	0	1	1

Step 4: Partitioning the RM

The reachability and antecedent set for each factor are determined with the help of final RM (Warfield, 1974; Farris and Sage, 1975). The reachability set consists of the factor (i) itself and the other factors which it may help achieve, whereas the antecedent set consists of the factor (i) itself and the other factors which may help in achieving it. After finding the reachability set and antecedent set for each factor, the intersection of these sets is determined from the factors and levels of different factors are determined. The factors for which the reachability set and an antecedent set having same value is placed at the top level in ISM hierarchy. Once the top level factors are identified, they are not considered further in determining the other top level factors of the remaining sub-graph. This procedure is repeated till all levels of the structure are identified. These identified levels help in the development of the digraph and the final model. The top level factor is positioned at the top of a digraph and so on. In the present case, 12 factors along with their reachability set, antecedent set, intersection set and levels are shown in Tables 4.5 - 4.10. Level identification process of these factors is completed in six iterations.

Table 4.5: Iteration 1

Factors	Reachability set	Antecedent set	Intersection set	Level
1	1	1,2,3,4,5,6,7,8,9,11,12	1	**I**
2	1,2,5,7,11	2,4,	2	
3	1,3,4,5,6,7,8,9,10,11,12	3,4	3,4	
4	1,2,3,4,5,6,7,8,9,10,11,12	3,4,10	3,4,10	
5	1,5,7,11	2,3,4,5,8,10	5	
6	1,6,9,11,12	3,4,6,8,9,10,	6,9	
7	1,7,11	2,3,4,5,7,8,9,10,11	7,11	
8	1,5,6,7,8,9,11	3,4,8,10	8	
9	1,6,7,9,11,12	3,4,6,8,9,10,	6,9	
10	4,5,6,7,8,9,10,11,12	3,4,10	4,10	
11	1,7,11	2,3,4,5,6,7,8,9,10,11	7,11	
12	1,11,12	3,4,6,9,10,12	12	

Table 4.6: Iteration 2

Factors	Reachability set	Antecedent set	Intersection set	Level
2	2,5,7,11	2,4,	2	
3	3,4,5,6,7,8,9,10,11,12	3,4	3,4	
4	2,3,4,5,6,7,8,9,10,11,12	3,4,10	3,4,10	
5	5,7,11	2,3,4,5,8,10	5	
6	6,9,11,12	3,4,6,8,9,10,	6,9	
7	7,11	2,3,4,5,7,8,9,10,11	7,11	**II**
8	5,6,7,8,9,11	3,4,8,10	8	
9	6,7,9,11,12	3,4,6,8,9,10,	6,9	
10	4,5,6,7,8,9,10,11,12	3,4,10	4,10	
11	7,11	2,3,4,5,6,7,8,9,10,11	7,11	**II**
12	11,12	3,4,6,9,10,12	12	

Table 4.7: Iteration 3

Factors	Reachability set	Antecedent set	Intersection set	Level
2	2,5	2,4	2	
3	3,4,5,6,8,9,10,12	3,4	3,4	
4	2,3,4,5,6,8,9,10,12	3,4,10	3,4,10	
5	5	2,3,4,5,8,10	5	**III**

Factors	Reachability set	Antecedent set	Intersection set	Level
6	6,9,12	3,4,6,8,9,10	6,9	
8	5,6,8,9	3,4,8,10	8	
9	6,9,12	3,4,6,8,9,10	6,9	
10	4,5,6,8,9,10,12	3,4,10	4,10	
12	12	3,4,6,9,10,12	12	**III**

Table 4.8: Iteration 4

Factors	Reachability set	Antecedent set	Intersection set	Level
2	2	2,4	2	**IV**
3	3,4,6,8,9,10	3,4	3,4	
4	2,3,4,6,8,9,10	3,4,10	3,4,10	
6	6,9	3,4,6,8,9,10	6,9	**IV**
8	6,8,9	3,4,8,10	8	
9	6,9	3,4,6,8,9,10	6,9	**IV**
10	4,6,8,9,10	3,4,10	4,10	

Table 4.9: Iteration 5

Factors	Reachability set	Antecedent set	Intersection set	Level
3	3,4,8,10	3,4	3,4	
4	3,4,8,10	3,4,10	3,4,10	
8	8	3,4,8,10	8	**V**
10	4,8,10	3,4,10	4,10	

Table 4.10: Iteration 6

Factors	Reachability set	Antecedent set	Intersection set	Level
3	3,4,10	3,4	3,4	
4	3,4,10	3,4,10	3,4,10	**VI**
10	4,10	3,4,10	4,10	**VI**

Step 5: Development of Conical Matrix

In this step, the factors in the same level are clubbed together across rows and columns of the final RM, and a conical matrix is developed as shown in Table 4.11. By adding up the number of ones in the rows and columns, the driver power and dependence power of different factors are computed respectively. Highest rank is given to the factors having the maximum number of ones in the rows and columns for ranking the drive power and dependence power respectively.

Table 4.11: Conical Matrix

Factors	1	7	11	5	12	2	6	9	8	3	4	10	Drive Power
1	1	0	0	0	0	0	0	0	0	0	0	0	1
7	1	1	1	0	0	0	0	0	0	0	0	0	3
11	1	1	1	0	0	0	0	0	0	0	0	0	3
5	1	1	1	1	0	0	0	0	0	0	0	0	4
12	1	0	1	0	1	0	0	0	0	0	0	0	3
2	1	1	1	1	0	1	0	0	0	0	0	0	5
6	1	0	1	0	1	0	1	1	0	0	0	0	5
9	1	1	1	0	1	0	1	1	0	0	0	0	6
8	1	1	1	1	0	0	1	1	1	0	0	0	7
3	1	1	1	1	1	0	1	1	1	1	1	1	11
4	1	1	1	1	1	1	1	1	1	1	1	1	12
10	0	1	1	1	1	0	1	1	1	0	1	1	9
Dependence Power	11	9	11	6	6	2	6	6	4	2	3	3	

Step 6: Development of Digraph

On the basis of the conical matrix, an initial digraph with transitivity links is developed. This digraph consists of nodes and lines of edges. A final digraph is developed by removing the indirect links as shown in Figure 4.2. In generating the digraph, the top level factor is placed at the top of the digraph and second level factor is positioned at the second position and so on, until the bottom level is placed at the lowest position in the digraph.

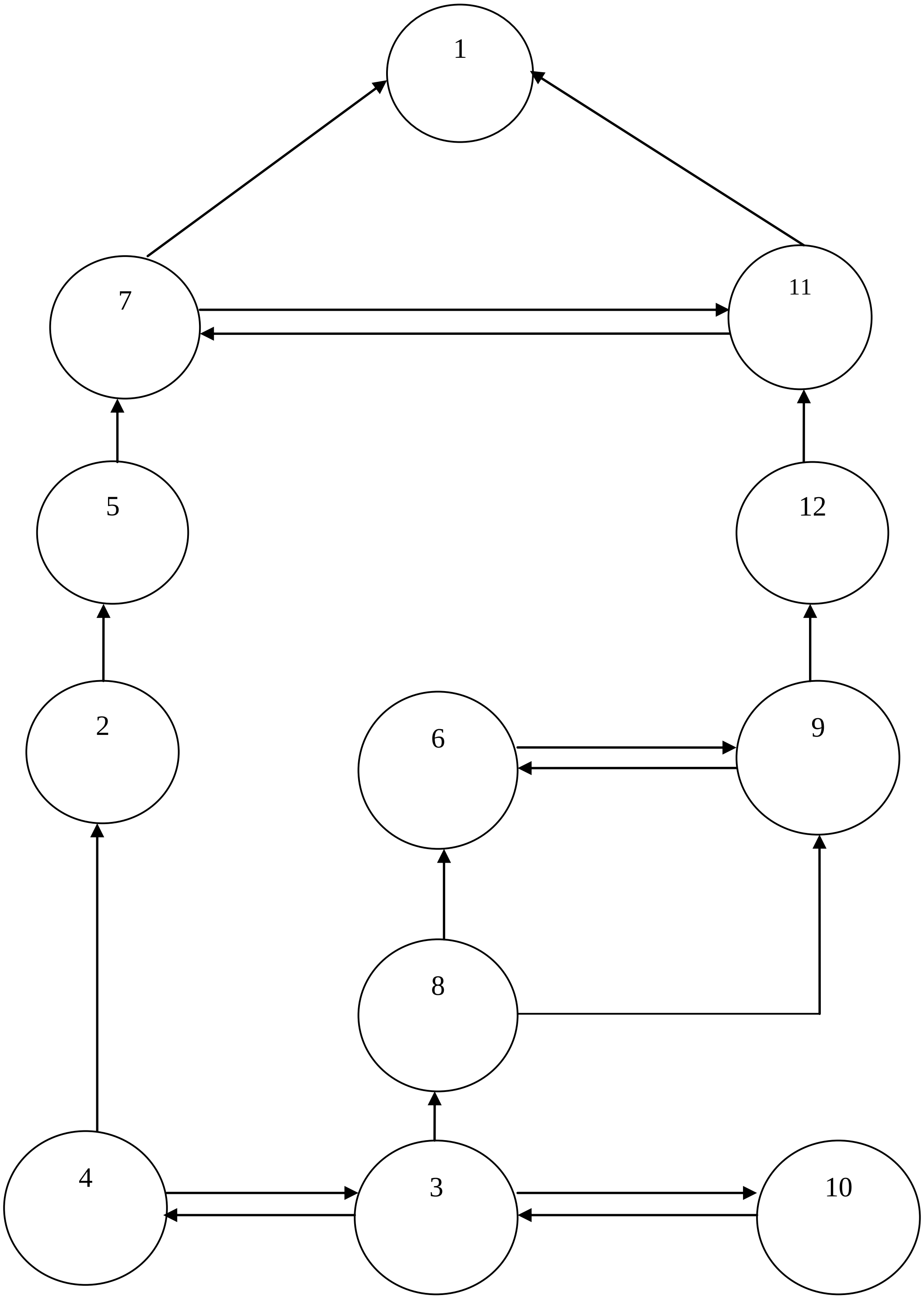


Figure 4.2: Digraph showing the levels of flexibility factors

Step 7: Development of ISM Model

Next, ISM model is developed from the final digraph by replacing nodes of the elements with statements as shown in Figure 4.3.

Step 8: Check for conceptual inconsistency

Conceptual inconsistency is checked by identifying and removing the intransitivity in the model.

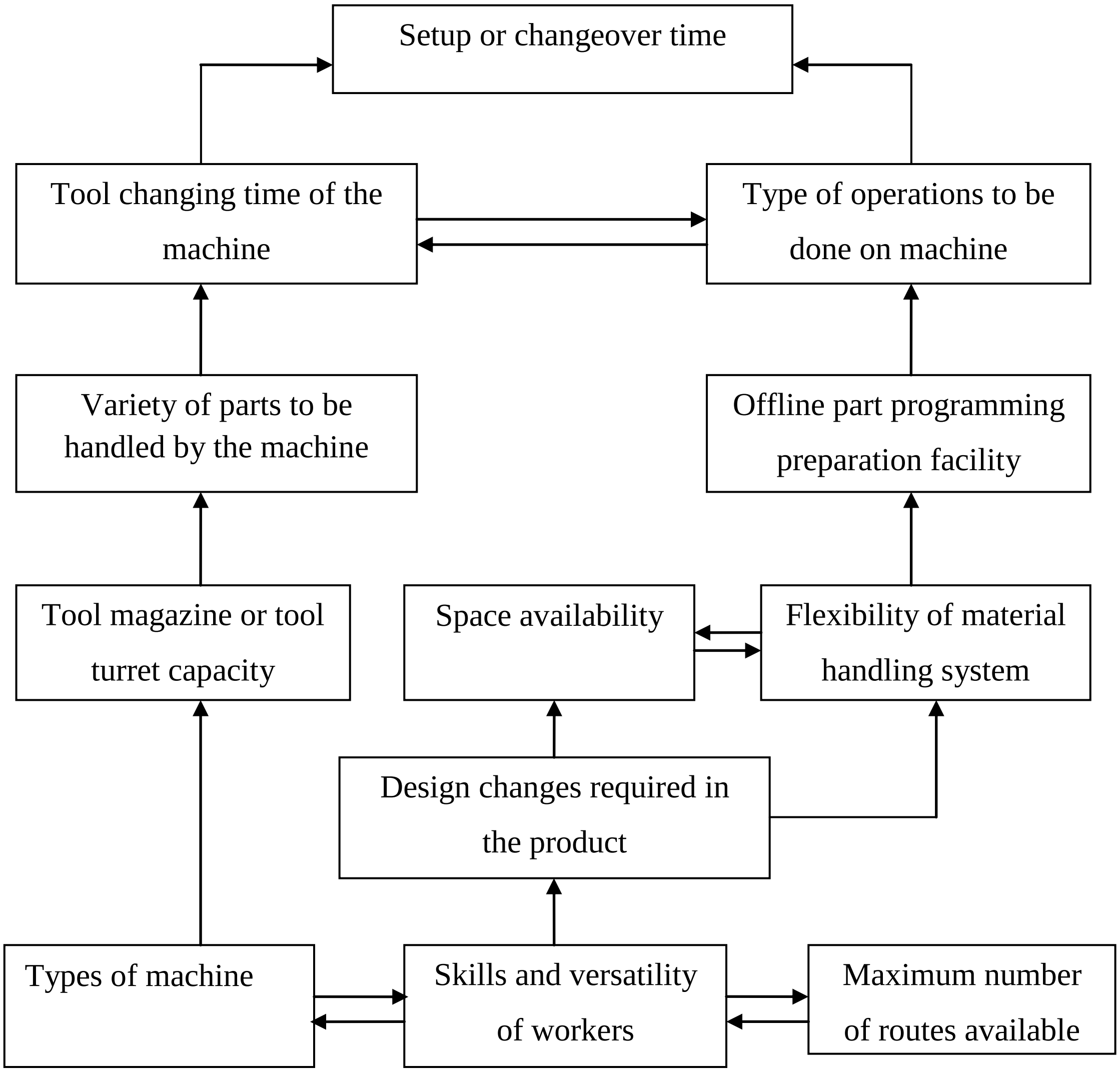


Figure 4.3: ISM model showing the levels of factors affecting FMS flexibility

4.3 MICMAC ANALYSIS

On the basis of dependence and driving power of different factors, MICMAC analysis is done MICMAC is based on multiplication properties of matrices (Sharma et al., 1995). MICMAC was first proposed by Duperrin and Godet (1973). On the basis of driving and dependence power of different factors, a classification was proposed by Singh and Kant (2008). So, all the factors affecting flexibility have been classified depending on their driving and dependence power. In this classification, four categories have been provided including autonomous factors, linkage factors, dependent factors and independent factors. For partitioning the graph, a similar approach has been utilized by a number of authors in their research work (Raj et al., 2012; Verma, 2014; Kumar and Sharma, 2015; Attri, 2013a; Jain and Raj, 2015). On the basis of dependence and driving power obtained in the present case, different factors have been classified into four categories as discussed below:

1. **Autonomous factors:** Because of weak dependence and weak driving power of the considered factors, they do not have much impact on the flexibility. Therefore, management should focus on all other factors.
2. **Linkage factors:** These factors have the strong drive power as well as strong dependence power. They are also unstable. Any action on them will have an effect on others and also a feedback effect on themselves.
3. **Dependent factors:** The factors of this category have weak drive power but strong dependence power.
4. **Independent factors:** These factors have strong drive power but weak dependence power. The factors with very strong drive power are generally considered as ‘key factors’ falls into the category of independent or linkage.

Different factors with their drive power and dependence power are shown in Table 4.11. After this, the drive power and dependence power matrix is developed as shown in Table 4.12. From Table 4.11, it is observed that factor 10 has drive power of 9 and dependence power of 3, hence in Table 4.12, it is placed at a position which corresponds to drive power of 9 and dependence power of 3, i.e., in the fourth cluster. Now its position in the fourth cluster shows that it is an independent factor. Similarly, all the factors are positioned corresponding to their driving power and dependence power.

Table 4.12: Drive power-dependent power matrix

Driving Power

12			4									
11		3	**IV**									
10									**III**			
9			10									
8												
7				8								
6						9						
5		2	**I**			6			**II**			
4						5						
3						12			7		11	
2												
1											1	
	1	2	3	4	5	6	7	8	9	10	11	12

Dependence Power

4.4 EVALUATION OF EFFECTIVENESS INDEX

The factors with their mean score and rank as shown in Table 4.1 are used for calculating the EI. After ranking the factors, inverse rank and weight for each factor have to be determined. Five point Likert's scale is used for assigning weights to different factors. The highest and lowest values of Likert's scale i.e., 5 and 1 are treated as 100% and 0% respectively. For each of the issues of effectiveness, a weight is assigned. The criteria for weight (W_i) is as under:

W_i = +1 (Strength), when percentage score > 60% (When LogK_i value is greater than 0.6).

= 0 (Neutral), when percentage score is between 40-60% (When LogK_i value is between 0.6 and 0.4).

= –1(Weakness), when percentage score < 40% (When LogK_i value is less than 0.4).

This framework was given by Cleveland et al. (1989), where C_j = Sum [W_i * Log K_i]. Chand et al. (2014, 2015) and Chand and Singh (2010) have also used this model for study the select issues of supply chain management (SCM).

Sum of entries of last column (W_i * Log K_i), give EI = 7.0569 as shown in Table 4.13. From the Table 4.13, theoretically, EI value may range between –8.7381 to +8.7381, which shows the minimum and maximum value of EI in the present case. This EI value helps the organizations to benchmark its performance against national and international standards. Here the qualitative values of the factors are converted into quantitative values, with the help of these values management can take the decision where there is a need for improvement.

Table 4.13: Measurement of EI

S.No.	**Factors affecting different flexibilities**	**Mean score**	**Rank**	**Inverse Rank**	**Log K_i**	**Weight (W_i)**	**W_i *LogK_i**
1	Setup or changeover time	4.35	1	12	1.0791	1	1.0791
2	Tool magazine or tool turret capacity	4.33	2	11	1.0414	1	1.0414
3	Skills and versatility of workers in the system	4.31	3	10	1	1	1
4	Type of machines	4.27	4	9	0.9542	1	0.9542
5	Variety of parts to be handled by the machine	4.2	5	8	0.9031	1	0.9031
6	Space availability	4.2	6	7	0.9031	1	0.9031
7	Tool changing time of the machine	4.17	7	6	0.7781	1	0.7781

S.No.	**Factors affecting different flexibilities**	**Mean score**	**Rank**	**Inverse Rank**	**Log K_i**	**Weight (W_i)**	**W_i *LogK_i**
8	Design changes required in the product	4.17	8	5	0.6989	1	0.6989
9	Flexibility of material handling system	4.15	9	4	0.6021	0	0
10	Maximum number of routes available	4.12	10	3	0.4771	0	0
11	Type of operations to be done on the machine	4.11	11	2	0.301	-1	-0.301
12	Offline part programming preparation facility	4.11	12	1	0	-1	0

4.5 RESULT AND DISCUSSION

The main purpose of this research is to identify the factors, which significantly affect the flexibility of FMS, so that the management can effectively deal with these factors. In this chapter, a survey has been used to rank the importance of the factors through the perception of the respondents. To analyze the interrelationship between these factors, an ISM model has been developed. The drive power-dependent power matrix (Table 4.12) gives some valuable sights about the relative importance and inter-dependence among the FMS factors.

The important managerial implications emerging from this chapter are as follows:

- Table 4.12 shows that there are five autonomous factor, i.e., ‘tool magazine or tool turret capacity’ (factor 2), ‘variety of parts to be handled by the machine’ (factor 5), ‘space availability’ (factor 6), ‘flexibility of material handling system’ (factor 9) and ‘offline part programming preparation facility’ (factor 12) which affect the flexibility of FMS. These autonomous factors have weak driving and weak dependent power and do not have much influence on the flexibility, so management should focus on all other factors.
- Dependent factors are ‘setup or changeover time’ (factor 1), ‘tool changing time of the machine’ (factor 7) and ‘type of operation to be done on machine’ (factor 11). These

factors are weak drivers but strongly depend on one another. So, the managers should pay attention to these factors.

- There is no factor in the third cluster, i.e. linkage factor. This shows that all the factors stated above are stable.
- Factors ‘skills and versatility of workers’ (factor 3), ‘type of machine’ (factor 4), ‘design changes required in the product’ (factor 8) and ‘maximum number of routes available’ (factor 10) are independent factors, i.e., they have strong driving power and weak dependency on other factors. They may be considered as the ‘key factors’ for affecting the flexibility of FMS.

Based on the response from questionnaire survey on various factors, EI for the factors affecting flexibility in FMS has been evaluated as shown in Table 4.13. Here the qualitative values of the factors are converted into quantitative values, with the help of these values management can take the decision where there is a need for improvement. From the Table 4.13, it has been observed that organisations are doing quite well in terms of setup time, tool magazine, skills and versatility of workers, types of machine, variety of parts to be handled by machine, space availability, tool changing time and design changes in product, however, there is need for improvement in area of flexibility of MHS, number of routes available, types of operations to be done on machine and offline part programming preparation facility related problems for dealing well with the flexibility affecting factors considered in this chapter. The maximum value of EI can reach up to 8.7381, in present case EI has been found to be 7.0569, and this value of EI is quite high. The EI evaluated can be utilized by the industries to benchmark their performance by focusing on the factors. With the help of EI and MICMAC analysis, the relative importance, interdependencies among the factors and the need of improvement could be known so that management could take the actions accordingly.

4.6 CONCLUSION

In this chapter, an ISM model has been used to demonstrate the interpretation of flexibility factors with the help of their driving and dependence power. The factors having high driving power must be controlled on a priority basis because there are few other dependent factors being affected by them. The ISM results provide strategic insight also. This study has strong implications for researchers as well as manufacturing managers. The researchers can identify some other issues, which may be important in addressing these factors. This study will help the manufacturing managers in understanding these factors, their relative importance and interdependencies. On the basis of which, they can take the decisions in order to overcome these factors affecting the flexibility of FMS. The combined approach of ISM and EI strengthens the realistic views of manufacturing managers and represents a clear image of the impact of different factors. In this way, different factors can be identified and dealt with utmost care.

CHAPTER V

PRIORITIZING THE PERFORMANCE MEASURES OF FMS USING MCDM APPROACHES

5.1 INTRODUCTION

In today's highly competitive business environment, survival and growth of manufacturing organizations depend on their ability to offer a great variety of high-quality products at an acceptable price using minimum lead time (Singh and Ahuja, 2015). Unpredictable market changes have been seen in the last few years and in order to survive in such a dynamic environment, manufacturing companies need to be flexible, adaptive, responsive to changes, and proactive also (Nagalingam and Lin, 2008). They should have the capability to handle a diverse range of products at a faster rate with low cost. In current scenario, to accomplish the challenges such as rapidly changing requirements of the customers, to adapt to the market changes, reducing the products and services costs to capture more market shares etc., most of the industries have to switch over to FMS in order to manufacture consistently good quality and cost effective products (Shivhare and Bansal, 2014). Therefore, the flexible automation is adopted by industries at a faster rate, and a large amount of money is being invested by the industries worldwide in FMS (Borenstien, 2000). FMSs can be utilized to deal with dynamic and uncertain production conditions (Singholi et al., 2012). FMS emerged as a powerful tool due to its wide flexibility, which is essential to stay competitive in this highly dynamic environment (Reddy and Rao, 2011).

Performance is directly related to the capability a manufacturing system in handling new and unpredictable products at lower costs while maintaining a short lead time. In order to achieve the best possible performance within given constraints, manufacturing industries are faced with the need to optimize the way in which they function (Ayag, 2002). Implementation of FMS results in high flexibility, enhanced efficiency, high-quality and reduced WIP inventory which are essential to respond quickly to the changing market requirements (Womack et al., 1990; Jang et al., 1996). In recent studies related to the FMS, researchers have been very eager to improve the performance of FMS (Wadhwa et al., 2005; Chan, 2003). Foster and Horngren (1988) stated that an FMS is related with performance measures focused on time, quality, operating efficiency, and flexibility. To deal with the increasingly uncertain external environment, manufacturing flexibility has become a significant dimension (Eraslan and Dagdeviren, 2010). Singholi et al. (2012, 2013) discussed the effects of manufacturing flexibilities on the performance of an FMS. They used the Taguchi experimental design methodology for evaluation of varying levels of machine and routing flexibility on the performance of FMS.

The objective of this chapter is to develop a framework for evaluating the performance of FMS. Due to the complexity of the relations between various performance measures of a manufacturing system, it is very difficult to assess them. An appropriate methodology should be used to handle such a situation. This study aims at the performance enhancement of manufacturing systems in Indian industry. Evaluation of performance is done by GTA, SAW and WPM. The performance measures' weights are calculated by using AHP, which are used later in SAW and WPM. The main research objectives of this chapter are:

- To identify the performance measures and sub-measures which are associated with the performance of FMS.
- To understand the relationship between these measures and sub-measures using digraphs and AHP.
- To evaluate the single numerical value named 'IOP' using matrix method and
- To evaluate the performance by using SAW and WPM.

5.2 IDENTIFICATION OF PERFORMANCE MEASURES OF FMS

There are various factors which could affect the performance of the FMS. Therefore, it is necessary to identify and analyze these factors affecting the performance of the FMS. Through the literature review, questionnaire survey and interactions with practicing managers and academicians, most significant performance measures which could affect the performance of FMS have been identified and presented in Table 5.1. If the number of sub-measures are large (25 in the present case), it becomes very complicated to figure out their quantification by GTA, SAW, and WPM. Therefore, these performance measures have been grouped into five major categories to prioritize their performance and to calculate the permanent value (function) without much difficulty.

Table 5.1: Performance measures and sub-measures with their references/resources

Performance Measures	References/ Sources
Measures related to Finance: P_1	
Return on investment (ROI) (P_{11})	Cordero (1997); Smith and Wright (2004)
High-profit margins (P_{12})	Expert opinion
Costs of sold goods (P_{13})	Hottenstein and Casey (1997); Groover (2001); Rosnah et al. (2003)
Growth in market share (P_{14})	Groover (2001)
Measures related to Customers: P_2	
Life of product (P_{21})	Expert opinion
Customer satisfaction (P_{22})	Heskett et al. (1994); Anderson et al. (1997)
After delivery services (P_{23})	Heskett et al. (1994); Keane and Wang (1995)
Maintenance cost (P_{24})	Rao and Padmanabhan (2006); Raj et al. (2008b); Nagar and Raj (2012)
Cost of product (P_{25})	Groover (2001); Hottenstein and Casey (1997); Rosnah et al. (2003)
Measures related to internal Business: P_3	
Reduction in WIP and queues (P_{31})	Nagar and Raj (2012); Groover (2003)
Assets utilization (P_{32})	Kaighobadi and Venkatesh (1994); Bayazit (2005); Groover (2003)
Flexible environment (P_{33})	Expert opinion
Throughput time (P_{34})	Kost and Zdanowicz (2005)
Reduced waste (P_{35})	Groover (2003)

Performance Measures	**References/ Sources**
Measures related to innovation and knowledge: P_4	
Awareness of challenges ahead (P_{41})	Expert opinion
Dynamic and proficient management (P_{42})	Expert opinion
Product innovation (P_{43})	Primrose and Verter (1996)
Process innovation (P_{44})	Expert opinion
Accurate data and information system (P_{45})	Masters (1996); Rad (2005)
Operational measures: P_5	
Processing time (P_{51})	Mosconi and Mcnair (1987); Johnson (1988)
Type and number of operations (P_{52})	Groover (2003); Verma et al. (2011)
Routing flexibility (P_{53})	De Meyer et al. (1989); Nagar and Raj (2012)
Multi-functional machines (P_{54})	Verma et al. (2011); Pandey et al. (2016)
Number of parts produced (P_{55})	Bayazit (2005)
Lead time (P_{56})	Groover (2001); Nagar and Raj (2012); Zhang et al. (2002)

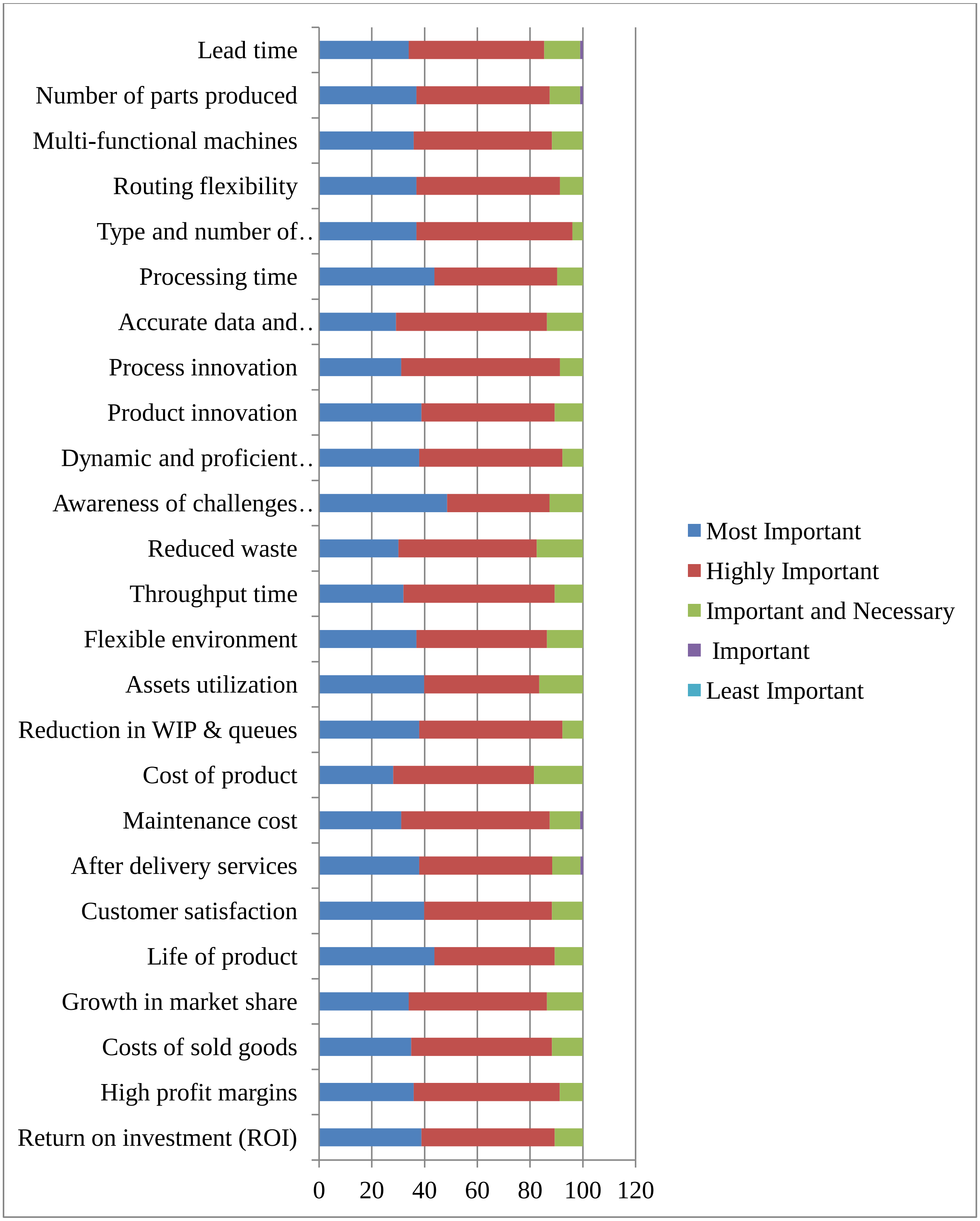


Figure 5.1: Sub-measures which will be used to evaluate the performance

5.3 METHODOLOGIES

Multi-criteria decision making (MCDM) analysis is an optimization technique which is applied to identify the most preferred alternative under multiple criteria. In the literature, a number of MCDM approaches are available such as GTA, compromise ranking method (VIKOR), AHP, ANP, multi-objective optimization by ratio analysis (MOORA), SAW, WPM, etc., for order preferences. In this chapter, GTA, SAW, and WPM are used for prioritization of performance measures, and permanent value (function) is calculated with the help of GTA approach.

5.3.1 GTA/Digraph and Matrix Approach

GTMA is a multiple attribute decision making (MADM) methodology used to determine the intensity of measures in an industry (Jain and Raj, 2015). Digraph and matrix approach has the capability to tackle a complex situation. Digraph and matrix approach is one of such methodology to evaluate the performance of the FMS because it allows the modeling of inter-dependence of measures under consideration, visual analysis, computer processing and also presents a single numerical index for all the measures (Raj et al., 2010). It is a systematically and logical approach. The advance theory of digraphs and its applications are very well documented. For modeling and analyzing different types of systems and problems, digraph model representation has proven to be very helpful in numerous fields of science and technology (Deo, 1999; Rao and Gandhi, 2002a).

5.3.1.1 Digraph Representation of Performance Measures and Sub-measures

The digraph is the visual demonstration of the measures, sub-measures and their interdependencies in terms of nodes and edges. In the case of an undirected graph, no direction is assigned to the edges in the graph, whereas in directed graphs or digraphs, direction is assigned to the edges based on their interdependencies. The digraph consists of a set of nodes $N = \{n_i\}$, with $i = 1,2,3,\ldots\ldots,X$ and a set of directed edges $P = \{p_{ij}\}$. A node n_i represents the i-th measure, and the edges correspond to the interdependence among measures. The number of considered nodes X is equal to the number of measures considered for the performance evaluation of FMS. If a node i has an impact over another node j, then a directed edge is drawn from node i to node j

(*i.e.*, p_{ij}). If a node *j* has an impact over *i*, then a directed edge is drawn from node *j* to node *i* (*i.e.*, p_{ji}).

To develop the 'FMS performance measure' digraph, the five categories of measures (as discussed above) are considered and represented by five nodes in the 'FMS performance measure' digraph as shown in Figure 5.2. The directed edges are drawn on the basis of interdependence of these performance measures. For example, financial measure has an impact on the customer, internal business, innovation and knowledge and operational measure; hence, directed edges are drawn from P_1 to P_2, P_3, P_4 and P_5. Similarly, other directed edges are drawn, and the digraph is developed, as shown in Figure 5.2. Depending on the relationship between different performance measures and sub-measures, the digraphs have been drawn as shown in Figures 5.2 to 5.7. These digraphs help in visualizing and analyzing the performance measures of FMS. These digraphs become complicated if the number of nodes and their interdependence increases and visual analysis also become complex and difficult to understand. To overcome this complexity, the digraph is represented in matrix form.

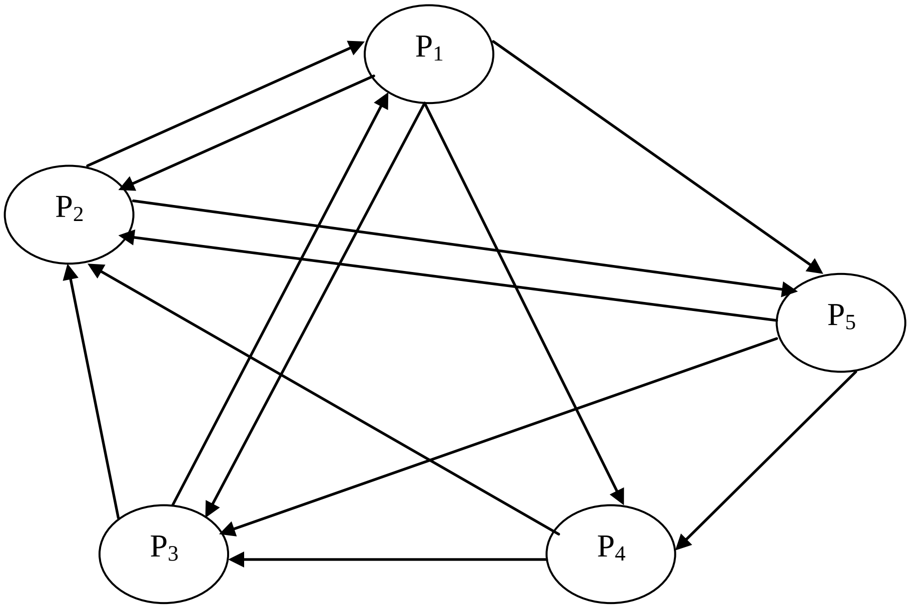


Figure 5.2: Digraph for performance measures (P)

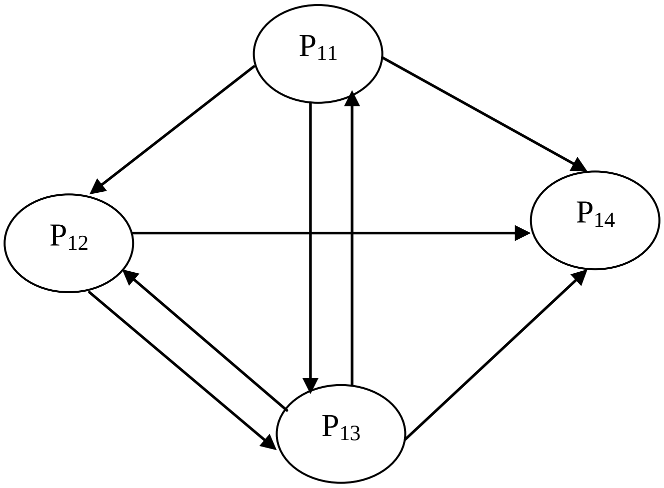


Figure 5.3: Digraph for sub-measures (P_1)

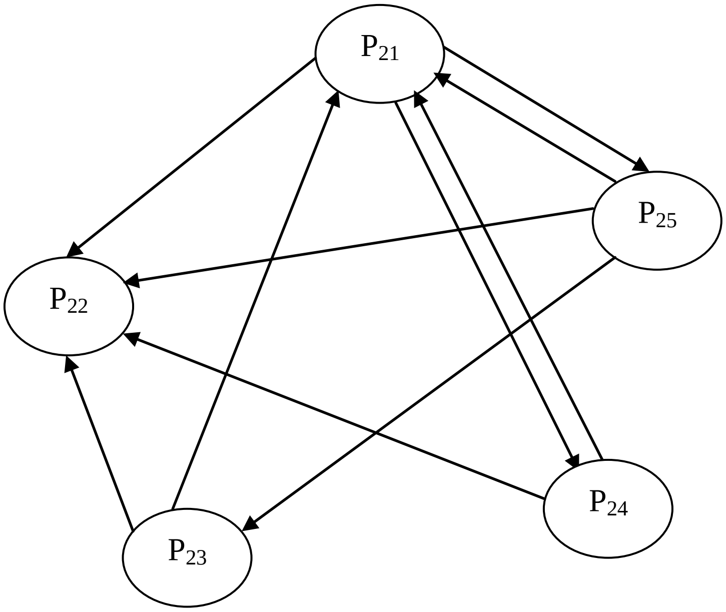


Figure 5.4: Digraph for sub-measures (P_2)

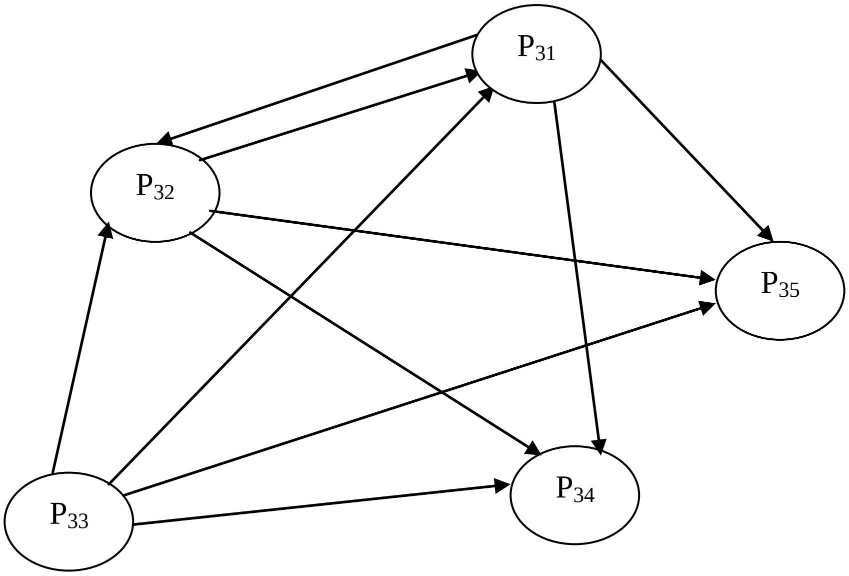


Figure 5.5: Digraph for sub-measures (P_3)

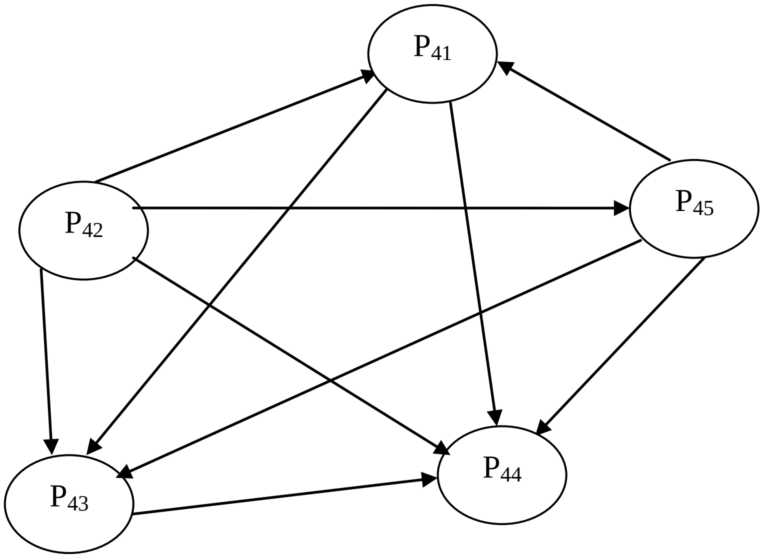


Figure 5.6: Digraph for sub-measures (P_4)

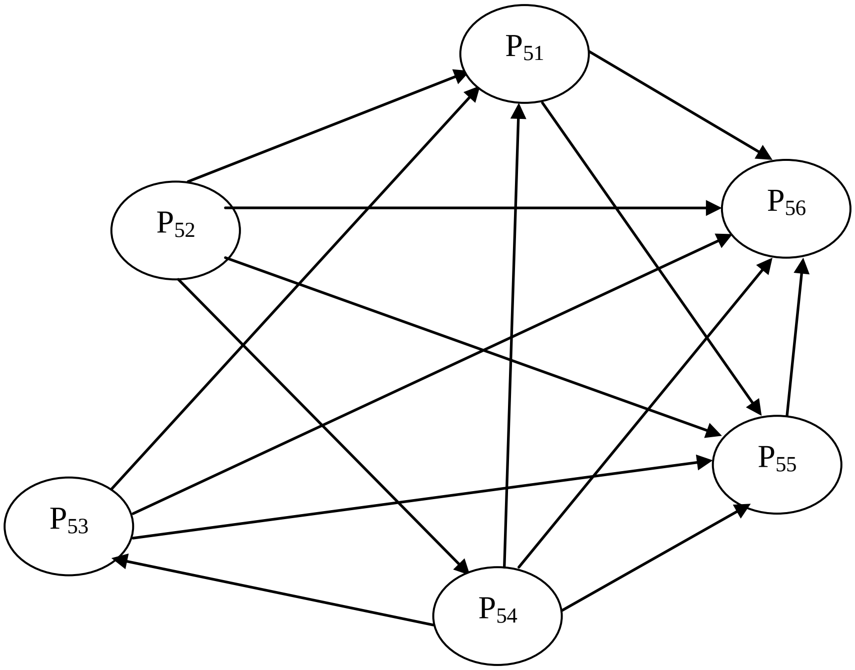


Figure 5.7: Digraph for sub-measures (P_5)

5.3.1.2 Matrix Representation of Performance Measures and Sub-measures

The digraph is converted into mathematical form with the help of matrix. The digraphs are well suited for visual study, but for computer processing, matrix representations have been considered as a better option. In order to represent the digraphs to a computer, the matrices have been proven very useful and convenient way. Matrices lend themselves easily to mechanical manipulations. Matrix representation of the digraph for FMS performance evaluation provides one-to-one representation. This matrix is called FMS performance evaluation matrix. This matrix is an M × M matrix and considers all the performance measures (P_i) and their relative importance (i.e., P_{ij}). The matrix has been derived to calculate the index using Tables 5.2 and Table 5.3. The diagonal elements are P_i and the non-diagonal elements are represented as P_{ij}. The value of the permanent function for all five sub-measures is calculated and used to evaluate the overall inter-dependencies.

Table 5.2: Quantification of performance measures (P_i's)

S.No.	Qualitative measure of performance measures	Value assigned
1	Exceptionally low	1
2	Very low	2
3	Low	3
4	Below average	4
5	Average	5
6	Above average	6
7	High	7
8	Very high	8
9	Exceptionally high	9

Table 5.3: Quantification of interdependencies/off-diagonal elements (P_{ij}'s)

S.No.	Qualitative measure of inter-dependencies	Value assigned
1	Very weak	1
2	Weak	2
3	Medium	3
4	Strong	4
5	Very strong	5

5.3.1.3 Permanent Function Representation of Performance Measures' Matrix

Both digraph and matrix representations are not solely in nature because they are altered by changing the labels of their nodes. Hence, to develop a unique representation that is independent of labeling, a permanent function of the FMS performance measures matrix is proposed here. This permanent function is a standard matrix function and is used in combinatorial mathematics (Jurkat and Ryser, 1966). The permanent function is calculated in a similar manner as its determinant. A negative sign appears in the calculation of determinant while in the permanent, i.e. the variable permanent function, positive signs reduce these negative signs. The permanent function does not involve any negative sign and, thus, no information is lost. The FMS performance measures function for matrix P* is written as:

$$
\begin{aligned}
\mathrm{per}(P^*) = {} & \prod_{i=1}^{5} P_i + \sum_{i,j,k,l,m} (P_{ij}P_{ji}) P_k P_l P_m \\
& + \sum_{i,j,k,l,m} (P_{ij}P_{jk}P_{ki} + P_{ik}P_{kj}P_{ji}) P_l P_m \\
& + \left(\sum_{i,j,k,l,m} (P_{ij}P_{ji})(P_{kl}P_{lk}) P_m + \sum_{i,j,k,l,m} (P_{ij}P_{jk}P_{kl}P_{li} + P_{il}P_{lk}P_{kj}P_{ji}) P_m \right) \\
& + \sum_{i,j,k,l,m} (P_{ij}P_{ji})(P_{kl}P_{lm}P_{mk} + P_{km}P_{ml}P_{lk}) \\
& + \sum_{i,j,k,l,m} (P_{ij}P_{jk}P_{kl}P_{lm}P_{mi} + P_{im}P_{ml}P_{lk}P_{kj}P_{ji}) \\
& + \sum_{i,j,k,l,m} (P_{ij}P_{ji})(P_{kl}P_{lm}P_{ik} + P_{km}P_{ml}P_{lk}) + \sum_{i,j,k,l,m} (P_{ij}P_{jk}P_{ki})(P_{lm}P_{mk}P_{kl}) \\
& + \sum_{i,j,k,l,m} (P_{ij}P_{ji})(P_{kl}P_{lk})(P_{ml}P_{mk}) \\
& + \sum_{i,j,k,l,m} (P_{ij}P_{jk}P_{kl}P_{lm}P_{mk} + P_{ml}P_{lk}P_{kj}P_{ji}P_{im}) \ldots\ldots\ldots\ldots \quad \text{(Equation 5.1)}
\end{aligned}
$$

The per(P*) is a mathematical expression in symbolic form, and it ensures an estimate of the important factors affecting the performance of an FMS. It is a complete expression for the evaluation of FMS performance as it considers the presence of all measures and their inter-dependencies. It contains a number of terms which are structure invariants. These terms are arranged in groupings whose physical significance is explained below:

- The first group represents the interactions of the five major performance measures (i.e., $P_1P_2P_3P_4P_5$).
- The second group is absent, as there is no self-loop in the digraph.
- Each term of the third group represents a two-element interdependence loop (i.e., P_{ij} P_{ji}) and the FMS measure of the remaining three unconnected elements.
- Each term of the fourth group represents a set of three-element interdependence loops (i.e., P_{ij} P_{jk} P_{ki} or P_{ik} P_{kj} P_{ji}) and the FMS measure of the remaining two unconnected elements.
- The fifth group contains terms arranged in two subgroups. The terms of the first subgroup consist of two-element interdependence loops (i.e., P_{ij} P_{ji} and P_{kl} P_{lk}) and one FMS performance measure, i.e., P_m. The terms of the second subgroup are a product of four-element interdependence loops (i.e., P_{ij} P_{jk} P_{kl} P_{li} or P_{il} P_{lk} P_{kj} P_{ji}) and one FMS performance measure, i.e., P_m.

- The terms of the sixth grouping are also arranged in two subgroups. The terms of the first subgroup are a product of a two-element interdependence loop (i.e., P_{ij} P_{ji}) and a three-element interdependence loop (i.e., P_{kl} P_{lm} P_{mk} or P_{km} P_{ml} P_{lk}). The second subgroup consists of terms that are a product of a five-element interdependence loops (i.e., P_{ij} P_{jk} P_{kl} P_{lm} P_{mi} or P_{im} P_{ml} P_{lk} P_{kj} P_{ji}).
- The terms of the seventh group are arranged in four subgroups. The first subgroup consists of terms that are a product of a two-element interdependence loop (i.e., P_{ij} P_{ji}) and a three-element interdependence loop (i.e., P_{kl} P_{lm} P_{ik} or P_{km} P_{ml} P_{lk}). The terms of the second subgroup are a product of two interdependence loops of three elements each (i.e., P_{ij} P_{jk} P_{ki} and P_{lm} P_{mk} P_{kl}). The terms of the third subgroup are a product of three interdependence loops of two elements each (P_{ij} P_{ji}, P_{kl} P_{lk} and P_{ml} P_{mk}). The fourth subgroup consists of a five-element interdependence loop (i.e., P_{ij} P_{jk} P_{kl} P_{lm} P_{mk} or P_{ml} P_{lk} P_{kj} P_{ji} P_{im}).

5.3.1.4 Evaluating the Index of Performance for FMS

Quantification of performance measures (i.e. P_i's) has been determined as shown in the last measure's matrix (P). Each category of measures has been identified as a sub-system, and the digraph and matrix method has been applied to each sub-system. The measure's sub-system has been evaluated for permanent function considering various measures affecting the sub-system. With the help of diagraphs, dependencies of measures at the sub-system level have been visualized. These digraphs lead to the inheritance of measures at the system level through matrix and measures. For each sub-system, their corresponding variable permanent matrices have been developed, and permanent function of these matrices has been computed. The permanent functions of these matrices will lead to inheritance of the performance measures. Thus, digraph and matrix method has been applied at every level. To obtain the complete value of multinomial, the diagonal as well as off-diagonal elements in per(P*), have been assigned some numerical values. Different measures have been represented by the diagonal elements and inter-dependencies among performance measures have been represented by off-diagonal elements. The numerical values have been assigned to different measures and sub-measures only after the discussion with a group of experts because the influence of all measures cannot be equal, and the inter-dependencies among measures at the system level cannot be measured directly. Two senior managers and two workers of a flexible manufacturing industry were considered in the experts' team. It was suggested to use Tables 5.2 and Table 5.3 for assigning these values. Since the performance is affected by a large number of factors, use of GTA approach at measures and sub-measures level leads to complexity. Thus under the dynamic condition, it is difficult to quantify the performance measures exactly. Hence, it is suggested to use Table 5.2 and Table 5.3 at sub-measures level. Further, a threshold value of the performance index may be set for the organization in similar fields. This will help an organization to access itself and improve.

It is enviable to determine the FMS performance quantitatively or qualitatively and in terms of an index also, to find out the intensity of different measures and sub-measures under consideration. The numerical value of the FMS performance is called index of performance. Although it is not an easy task to measure the FMS performance in quantitative terms, per(P*), i.e., equation (5.1) is a useful tool to quantify the FMS performance measures. It is a function of different performance measures, their inter-dependencies and complexities. Hence, the $(IOP)_{FMS}$ is given as:

$(IOP)_{FMS}$ = per(P*) = permanent function FMS performance measures matrix

The performance of any number of organizations can be determined by evaluating the $(IOP)_{FMS}$ value of those organizations. As in the multinomial expression (Equation 5.1), no negative terms are used, i.e., positive values of P_i and P_{ij} will result in a higher value of the $(IOP)_{FMS}$. A higher value of $(IOP)_{FMS}$ for any organization means higher performance rate of that industry. If $(IOP)_{FMS}$ value come out to be lower for any organization, it means that organization requires to improve its performance.

$$\text{Sub-measures} \qquad P_1 = \begin{array}{c|cccc|} & P_{11} & P_{12} & P_{13} & P_{14} \\ \hline P_{11} & 8 & 4 & 3 & 3 \\ P_{12} & 0 & 7 & 2 & 4 \\ P_{13} & 4 & 3 & 9 & 4 \\ P_{14} & 0 & 0 & 0 & 8 \\ \hline \end{array}$$

Sub-measures

$$P_2 = \begin{array}{c|ccccc|} & P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\ P_{21} & 8 & 4 & 0 & 3 & 3 \\ P_{22} & 0 & 9 & 0 & 0 & 0 \\ P_{23} & 3 & 3 & 6 & 0 & 0 \\ P_{24} & 3 & 2 & 0 & 7 & 0 \\ P_{25} & 3 & 4 & 2 & 0 & 8 \end{array}$$

Sub-measures

$$P_3 = \begin{array}{c|ccccc|} & P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \\ P_{31} & 7 & 2 & 0 & 3 & 2 \\ P_{32} & 4 & 9 & 0 & 3 & 2 \\ P_{33} & 3 & 4 & 7 & 2 & 3 \\ P_{34} & 0 & 0 & 0 & 8 & 0 \\ P_{35} & 0 & 0 & 0 & 0 & 6 \end{array}$$

Sub-measures

$$P_4 = \begin{array}{c|ccccc|} & P_{41} & P_{42} & P_{43} & P_{44} & P_{45} \\ P_{41} & 7 & 0 & 4 & 4 & 0 \\ P_{42} & 4 & 8 & 4 & 4 & 4 \\ P_{43} & 0 & 0 & 8 & 3 & 0 \\ P_{44} & 0 & 0 & 0 & 9 & 0 \\ P_{45} & 4 & 0 & 4 & 3 & 8 \end{array}$$

Sub-measures

$$P_5 = \begin{array}{c|cccccc|} & P_{51} & P_{52} & P_{53} & P_{54} & P_{55} & P_{56} \\ P_{51} & 7 & 0 & 0 & 0 & 2 & 3 \\ P_{52} & 4 & 8 & 3 & 3 & 4 & 3 \\ P_{53} & 3 & 0 & 8 & 0 & 2 & 3 \\ P_{54} & 3 & 0 & 2 & 7 & 3 & 4 \\ P_{55} & 0 & 0 & 0 & 0 & 6 & 4 \\ P_{56} & 0 & 0 & 0 & 0 & 0 & 8 \end{array}$$

Measures

$$P = \begin{array}{c|ccccc|} & P_1 & P_2 & P_3 & P_4 & P_5 \\ P_1 & 5344 & 3 & 3 & 4 & 3 \\ P_2 & 2 & 32616 & 0 & 0 & 2 \\ P_3 & 3 & 2 & 23856 & 0 & 0 \\ P_4 & 0 & 3 & 4 & 32256 & 0 \\ P_5 & 0 & 3 & 4 & 4 & 150528 \end{array}$$

The index of various performance measures has been determined. The values come out to be P^*_1=5344, P^*_2=32616, P^*_3=23856, P^*_4=32256, P^*_5=150528. These values of performance measures have been used to determine the overall system performance index as shown in the last measure matrix (P) and it comes out to be $(IOP)_{FMS} = 2.0189 \times 10^{22}$.

5.3.1.5 Range of $(IOP)_{FMS}$

The maximum and minimum values of $(IOP)_{FMS}$ for each measure and the overall system performance can be determined by taking into account the maximum and minimum values, respectively, for measures and their inter-dependencies. The inheritance of each measure depends upon its sub-measures, and the value of $(IOP)_{FMS}$ will be maximum when the inheritance of sub-measures is maximum. For example, the value of Per P_1* for the first category (i.e., financial measure) will be maximum when the inheritance of all its sub-measures is maximum, i.e., 9 (as per Table 5.2). Hence, the FMS measures' matrix for this category may be rewritten as:

Sub-measures of P_1

$$\begin{array}{c|cccc|} & P_{11} & P_{12} & P_{13} & P_{14} \\ P_{11} & 9 & 4 & 3 & 3 \\ P_{12} & 0 & 9 & 2 & 4 \\ P_{13} & 4 & 3 & 9 & 4 \\ P_{14} & 0 & 0 & 0 & 9 \end{array}$$

The maximum value of Per P_1* for the first category is 8307. The value of Per P_1* of the financial measures will be minimum when the inheritance of all its sub-measures is minimum, i.e., 1 (as per Table 5.2). Hence, the FMS measures' matrix for this category may be rewritten as:

Sub-measures of P_1

$$\begin{array}{c|cccc} & P_{11} & P_{12} & P_{13} & P_{14} \\ \hline P_{11} & 1 & 4 & 3 & 3 \\ P_{12} & 0 & 1 & 2 & 4 \\ P_{13} & 4 & 3 & 1 & 4 \\ P_{14} & 0 & 0 & 0 & 1 \end{array}$$

The minimum value of Per P_1* for the first category is 51. Similarly, the maximum and minimum values of each subsystem can be determined. Now, the maximum and minimum values (i.e., extreme limits) of $(IOP)_{FMS}$ for the system can be evaluated by considering the maximum and minimum values of all subsystems, respectively, and these limits are shown in Table 5.4. The extreme limits of $(IOP)_{FMS}$ indicate its range, which is utilized in determining the levels of performance of FMS as shown in Table 5.4.

Table 5.4: Maximum and minimum values of the permanent function

Permanent function at the subsystem/system level	Maximum value	Minimum value	Current value
Per P_1*	8307	51	5344
Per P_2*	73629	37	32616
Per P_3*	64881	9	23856
Per P_4*	59049	1	32256
Per P_5*	531441	1	150528
Per P*	1.24531×10^{24}	46204	2.0189×10^{22}

The $(IOP)_{FMS}$ value any industry can be determined by putting the values of P_i and P_{ij} in Equation (5.1). $(IOP)_{FMS}$ values will be different for different industries because of the existence of performance measures to a different level in them. So, based on the $(IOP)_{FMS}$ values of a number of industries, they may be ranked in ascending or descending order.

5.3.2 Simple Additive Weighting (SAW)

Two decision making approaches, which are SAW and WPM, are merged with AHP to obtain the best results. AHP has been utilized for computing the weights of different performance measures and sub-measures, so that they can be utilized later in SAW and WPM methods for prioritizing the performance measures in FMS. To change the qualitative measures into the quantitative measures, fuzzy logic has been used as shown in Table 5.5. Rao (2007) merged the information on fuzzy MCDM. Bellman and Zadeh (1970) firstly relate fuzzy set theory to decision-making problems. Chen and Hwang (1992) proposed the first conversion of linguistic terms into fuzzy numbers and then the fuzzy numbers into crisp scores. An 11-point scale used in the study has been shown in Figure 5.8.

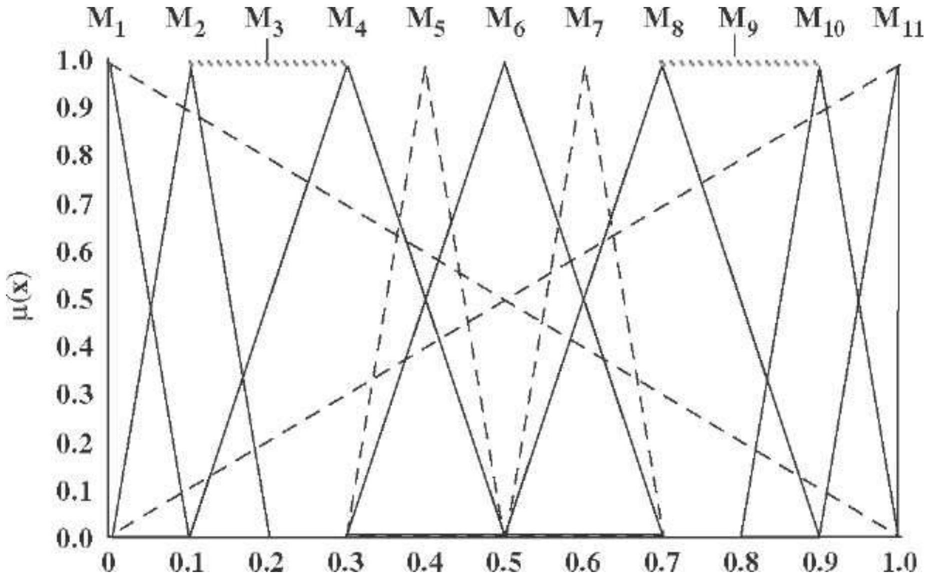


Figure 5.8: Linguistic term into their corresponding fuzzy numbers (11-point scale)

Table 5.5: Conversion of linguistic terms into fuzzy scores (Chen and Hwang, 1992)

Linguistic term	Fuzzy No.	Crisp No.
Exceptionally low	M1	0.045
Extremely low	M2	0.135
Very low	M3	0.255
Low	M4	0.335
Below average	M5	0.41
Average	M6	0.5
Above average	M7	0.59
High	M8	0.665
Very high	M9	0.745
Extremely high	M10	0.865
Exceptionally high	M11	0.955

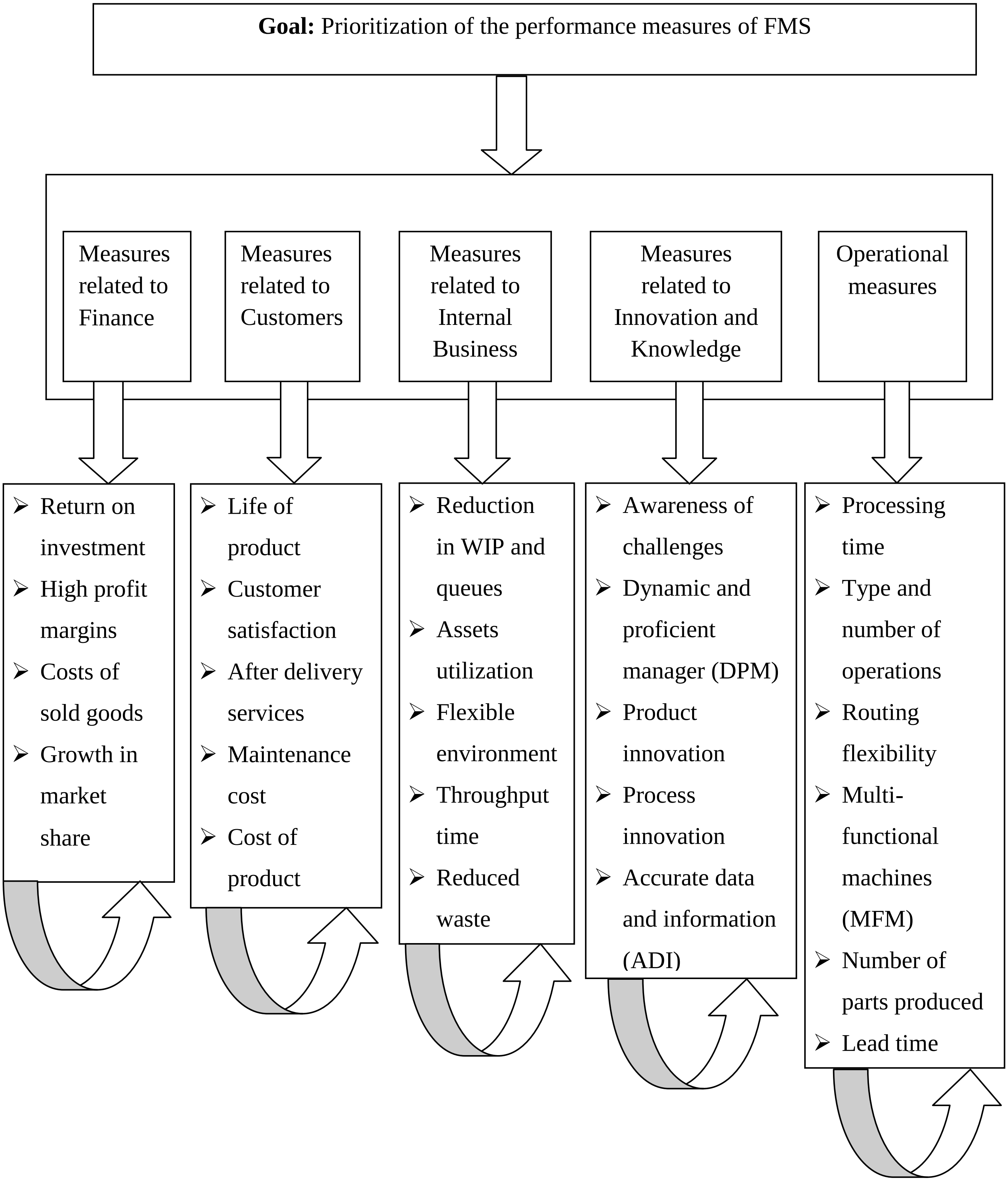


Figure 5.9: Hierarchy of performance measures in FMS

Various steps involved in the SAW approach are:

Step 1: In this step objective is determined, and the pertinent evaluation performance measures are identified. All measure and sub-measures are beneficial measures, i.e. higher values are desired. The hierarchy of performance measures is shown in Figure 5.9.

Step2: The weights are calculated with the help of AHP approach. The steps are explained below:

- Pairwise comparison matrices of measures are constructed by utilizing a scale of relative importance.
- Maximum Eigen value λ_{max}, consistency index CI = (λ_{max} - M) / (M -1) are determined. The smaller the value of CI, the smaller is the difference from the consistency.
- The value of random consistency index (RI) for the number of measures used in decision making is obtained, based on the order of matrix as shown in Table 5.6. It shows the value of RI for matrices of order 1 to 10 obtained by approximating random indices using a sample size of 500 (Saaty, 2000).

Table 5.6: Average random index (RI) based on matrix size

Size of Matrix (M)	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

- Consistency ratio CR = CI/RI is calculated for each matrix. Usually, a CR of 0.1 or less is considered as acceptable, and it reflects that the judgments made have a good consistency.

Pairwise comparison matrices for measures and sub-measures based on relative importance are shown in Table 5.7-5.12.

Table 5.7: Pairwise comparison of performance measures

Measures	Finance	Customers	Internal Business	Innovation and knowledge	Operational		Priority Vectors
Finance	1	1/2	2	1/2	1/2		0.140
Customers	2	1	2	2	1/2		0.243
Internal Business	1/2	1/2	1	3	1/3		0.140
Innovation and Knowledge	2	1/2	1/3	1	1/2		0.129
Operational	2	2	3	2	1		0.348

Eigen Value = 5.390, CI = 0.098, CR = 0.087

Table 5.8: Pairwise comparison of finance sub-measures

Finance	Return on investment	High-profit margins	Costs of sold goods	Growth in market share			Priority Vectors
Return on investment	1	1/3	3	3			0.267
High-profit margins	3	1	4	3			0.496
Costs of sold goods	1/3	1/4	1	1/3			0.083
Growth in market share	1/3	1/3	3	1			0.154

Eigen Value = 4.236, CI = 0.079, CR = 0.087

Table 5.9: Pairwise comparison of customers sub-measures

Customers	Life of product	Customer satisfaction	After delivery services	Maintenance cost	Cost of product		Priority Vectors
Life of product	1	3	4	3	4		0.432
Customer satisfaction	1/3	1	4	3	2		0.242
After delivery services	1/4	1/4	1	1/4	1/3		0.056
Maintenance cost	1/3	1/3	4	1	2		0.156
Cost of product	1/4	1/2	3	1/2	1		0.114

Eigen Value = 5.336, CI = 0.084, CR = 0.075

Table 5.10: Pairwise comparison of internal business sub-measures

Internal Business	Reduction in WIP and queues	Assets utilization	Flexible environment	Throughput time	Reduced waste		Priority Vectors
Reduction in WIP and queues	1	1/4	2	1/3	1/2		0.099
Assets utilization	4	1	4	3	3		0.440
Flexible environment	1/2	1/4	1	1/2	2		0.108
Throughput time	3	1/3	2	1	5		0.258
Reduced waste	2	1/3	1/2	1/5	1		0.095

Eigen Value = 5.406, CI = 0.102, CR = 0.091

Table 5.11: Pairwise comparison of innovation and knowledge sub-measures

Innovation and Knowledge	Awareness of challenges	DPM	Product innovation	Process innovation	ADI		Priority Vectors
Awareness of challenges	1	1/3	2	3	1/2		0.170
DPM	3	1	3	3	1/3		0.264
Product innovation	1/2	1/3	1	2	1/3		0.110
Process innovation	1/3	1/3	1/2	1	1/3		0.077
ADI	2	3	3	3	1		0.378

Eigen Value = 5.398, CI = 0.099, CR = 0.089

Table 5.12: Pairwise comparison of operational sub-measures

Operational	Processing time	Type and number of operations	Routing flexibility	MFM	Number of parts produced	Lead time	Priority Vectors
Processing time	1	3	3	4	4	4	0.388
Type and number of operations	1/3	1	3	2	3	1/2	0.162
Routing flexibility	1/3	1/3	1	4	4	1/2	0.132
MFM	1/4	1/2	1/4	1	3	1/3	0.076
Number of parts produced	1/4	1/3	1/4	1/3	1	1/3	0.049
Lead time	1/4	2	2	3	3	1	0.194

Eigen Value = 6.605, CI = 0.121, CR = 0.098

- Global weights are calculated to determine the normalized weights of the sub-measures as shown in Table 5.13.

Table 5.13: Sub-measures with their global weights

Measures	Priority Vectors	Sub-measures	Priority Vectors	Global Weights (G.W.)
Measures related to Finance	0.140	Return on investment (ROI)	0.267	0.037
		High-profit margins	0.496	0.070
		Costs of sold goods	0.083	0.012
		Growth in market share	0.154	0.022
Measures related to Customers	0.243	Life of product	0.432	0.105
		Customer satisfaction	0.242	0.059
		After delivery services	0.056	0.014
		Maintenance cost	0.156	0.038
		Cost of product	0.114	0.028
Measures related to Internal business	0.140	Reduction in WIP and queues	0.099	0.014
		Assets utilization	0.440	0.062
		Flexible environment	0.108	0.015
		Throughput time	0.258	0.036
		Reduced waste	0.095	0.013
Measures related to Innovation and knowledge	0.129	Awareness of challenges ahead	0.170	0.022
		DPM	0.264	0.034
		Product innovation	0.110	0.014
		Process innovation	0.077	0.010
		ADI	0.378	0.049
Operational measures	0.348	Processing time	0.388	0.135
		Type and number of machines	0.162	0.056
		Routing flexibility	0.132	0.046
		MFM	0.076	0.026
		Number of parts produced	0.049	0.017
		Lead time	0.194	0.068

Step 3: The qualitative sub-measures are converted to their corresponding fuzzy number and then to the corresponding crisp values.

Step 4: P_i value is calculated for each measure, by the following formula

$$P_i = \sum_{j=1}^{M} \left(w_j(m_{ij})\right) \qquad \text{(Equation 5.2)}$$

where w_j represents the global weights of sub-measures, m_{ij} represents the crisp value assigned to the sub-measures according to their importance within the corresponding measure and P_i is the overall or composite score of the measures. The measure with the highest value is considered as the first preference.

5.3.3 Weighted Product Method (WPM)

This method is similar to SAW. Miller and Starr (1969) stated that the major difference between SAW and WPM is that there was an addition in case of SAW method but in WPM, there is multiplication in the model. The overall or composite performance score of measures is evaluated as

$$P_i = \prod_{j=1}^{M} [(m_{ij})]^{w_j} \qquad \text{(Equation 5.3)}$$

As explained in step 3 of SAW method, the crisp values are determined in similar way. Each value of measure with respect to sub-measures, i.e., m_{ij} is raised to the power of the relative global weight of the corresponding sub-measure. The measure with the highest P_i value is considered as the first preference. All the sub-measures with their fuzzy crisp value, global weights and overall or composite score (P_i's) as obtained by SAW and WPM are shown in Table 5.14.

Table 5.14: Measures with their overall/composite score (P_i's) as obtained by SAW and WPM

Finance				
Sub-measures	**Fuzzy crisp value**	**G.W.**	**SAW**	**WPM**
ROI	0.745	0.037	0.028	0.989
High profit margins	0.745	0.070	0.052	0.980
Costs of sold goods	0.745	0.012	0.009	0.997
Growth in market share	0.665	0.022	0.014	0.991
Total			0.103	3.957
Customers				
Sub-measures	**Fuzzy crisp value**	**G.W.**	**SAW**	**WPM**
Life of product	0.955	0.105	0.100	0.995
Customer satisfaction	0.955	0.059	0.056	0.997
After delivery services	0.865	0.014	0.012	0.998
Maintenance cost	0.865	0.038	0.033	0.995
Cost of product	0.955	0.028	0.027	0.999
Total			0.227	4.984
Internal Business				
Sub-measures	**Fuzzy crisp value**	**G.W.**	**SAW**	**WPM**
Reduction in WIP and queues	0.665	0.014	0.009	0.995
Assets utilization	0.865	0.062	0.053	0.997
Flexible environment	0.665	0.015	0.010	0.998
Throughput time	0.665	0.036	0.024	0.995
Reduced waste	0.665	0.013	0.009	0.999
Total			0.105	4.959

Innovation and Knowledge

Sub-measures	Fuzzy crisp value	G.W.	SAW	WPM
Awareness of challenges	0.865	0.022	0.019	0.997
DPM	0.745	0.034	0.025	0.990
Product innovation	0.865	0.014	0.012	0.998
Process innovation	0.865	0.010	0.009	0.999
ADI	0.865	0.049	0.042	0.993
Total			0.107	4.976

Operational measures

Sub-measures	Fuzzy crisp value	G.W.	SAW	WPM
Processing time	0.745	0.135	0.101	0.961
Type and number of machines	0.745	0.056	0.042	0.984
Routing flexibility	0.745	0.046	0.034	0.987
MFM	0.865	0.026	0.022	0.996
Number of parts produced	0.865	0.017	0.015	0.998
Lead time	0.745	0.068	0.051	0.980
Total			0.264	5.905

5.4 DISCUSSION

The performance of FMS is affected by various performance measures. Hence, it becomes essential to quantify the effect of these measures on performance and know the exact nature of these measures. The research work presented in this chapter helps to accomplish these objectives significantly. A comparative study of MCDM approaches like GTA, SAW, and WPM for prioritization of various performance measures have been discussed in this chapter. The performance index has been evaluated with the help of GTA/ digraph and matrix approach. The evaluated IOP of various performance measures can be used by the managers to take precautions and decisions for handling these measures. The SAW and WPM methods have been integrated with AHP. AHP has been utilized for computing the weights of different measures to use them later in SAW and WPM approaches. Here, to change the qualitative measures into the quantitative measures, fuzzy logic has been used. First of all, qualitative measures have been converted to their corresponding fuzzy number, and then converted to the crisp values. Here, the measures affecting the performance of an FMS have been grouped into five categories namely Finance (P_1), Customers (P_2), Internal business (P_3), Innovation and knowledge (P_4) and Operational (P_5). GTA, SAW and WPM methodologies reveal that the operational measure has highest IOP and overall or composite score. Therefore, it is the most influencing measure affecting the FMS performance. The measures with their scores and prioritization obtained with SAW, WPM, and GTA have been shown in Table 5.15.

Table 5.15: Measures with their scores and prioritization

Performance Measures	SAW (P_i)	WPM (P_i)	GTA (IOP)	Prioritization/ Ranking
Measures related to Finance	0.103	3.957	5344	V
Measures related to Customers	0.227	4.984	32616	II
Measures related to Internal Business	0.105	4.959	23856	IV
Measures related to Innovation and Knowledge	0.107	4.976	32256	III
Operational measures	0.264	5.905	150528	I

5.5 CONCLUSION

The performance of FMS plays a very vital role in the survival of manufacturing industries because extensive competition in manufacturing has left no space for system inefficiencies. In this chapter, various measures and sub-measures affecting the performance of an FMS have been identified and analyzed. With the help of GTA, the operational measure has found with a maximum value of IOP. Same results have been found with SAW and WPM. Hence, it is suggested that operational measure and its sub-measures should be primarily taken care of, in improving the performance of FMS.

The results obtained from this research have important managerial implications. These methodologies can be utilized by the industrial managers to quantify the performance measures so that they could make the decisions regarding improvements required in their industries to enhance the performance. The performance of different industries can be compared with the help of the methodologies discussed here. These methodologies have been considered as the effective tools for evaluation, comparison, and ranking of FMS performance.

CHAPTER VI

OPTIMIZATION OF AGV’s PATH LAYOUT IN FMS

6.1 INTRODUCTION

To compete in the marketing globalization, manufacturing industries need to produce their goods, with high quality while maintaining low cost (Kaur et al., 2015). The development in the technology nowadays confronts manufacturing systems to a variety of alternatives for in-plant transportation. The MHS is proven to be the backbone of an FMS. The performance of the whole facility is directly affected by the performance of the MHS. With the current pressures on manufacturing companies to cut the costs, AGVS have proven themselves as an effective means of reduction in the cost of labour. In modem manufacturing systems, to enhance the flexibility in transporting the material between different workstations, AGVs are widely used as MHS in FMS. AGVs are fully automated, battery-powered vehicles that are able to transport goods in a logistic or production environment (Weyns and Holvoet, 2008).

In FMS, the main advantage of using AGVs as material handling is automated loading and unloading, ease of modification of the guide path network, computer control and flexibility in path movement. AGVS are much more flexible than other automated material handling devices such as conveyor systems and considered as the most flexible equipment of MHS. Applications of AGVS exist in all fields of industry and trade. These vehicles are controlled by a computer and operated with or without wire guidance along the flow path. When more than one vehicle is present in the system, the system controller is accountable for the traffic regulation. The direction of traffic can be either unidirectional or bidirectional along the flow path. The travel distance can be reduced by using bidirectional traffic flows, instead of unidirectional flows due to the possibility of making shortcuts in the path travelled. Due to the flexibility provided by AGVs, the flow path can easily be rearranged in case of changes in the production requirements. Advantages of using AGVS include: increased productivity, safety, and quality (Sule, 1988). Many more advantages of using AGVs are: lower workers compensation cost due to better environment, reduced product damage because of carefully calibrated and programmed movements of AGVs, avoided physical strain to workers, efficient material handling to enhance production, and accurate product tracking, etc.

The efficiency of an AGV system has large influence on the performance of FMS, therefore using suitable strategies which involve MHS with FMS simultaneously, one can increase flexibility and productivity and decrease the cost price per unit. The widespread use of AGVS in manufacturing and warehousing has boosted interest in the development of both simulation and analytical tools for designing in AGV system.

The guide path layout is one of the most significant variables in the design of AGVS. According to Kumar et al. (2015), the pattern of AGV guide path layout has become one of the major issues of concern in the AGV system. Wang and Chan (2014) also considered the fixed path layout of AGVs as one of the critical issue in the successful implementation of production processes and enhancing the system performance. This chapter is concerned with the issue of flow path design. Here zero-one linear integer programming approach has been chosen for developing the optimal flow path design. A conventional layout is used, and the unidirectional flow path is considered in this case. In a conventional layout, one or more AGVs are used, and they move from one station to another station along the arcs. One AGV may flow from one zone to another zone i.e. there is no control zone. The main research objectives of this chapter are:

- To determine various factors which affect the designing of AGV system
- To design industry based optimization technique for AGV path layouts using 0-1 linear integer programming with an objective of minimizing the total loaded transportation distance of AGVs.

6.2 REVIEWS ON PATH LAYOUT PROBLEMS

A large number of papers have been presented by numerous authors in the literature related to various AGV issues. But, within the scope of present research, only reviews on AGV path layout problems are considered. Several authors (Alam et al., 2015; Soolaki, 2013; Abbas et al., 2012; Pourrahimian et al., 2012; Falkner et al., 2010; Arora and Arora, 2010; Li et al., 2010) also used the linear integer programming in their research work for optimization in various fields. Some authors (Banerjee and Barai, 2007; Gaskins and Tanchoco, 1987; Gaskins et al., 1989; Goetz and Egbelu, 1990; Kaspi and Tanchoco, 1990; Sinriech and Tanchoco, 1993; Kim and Tanchoco, 1991) formulate the guide-path design problem as a 0-1 integer-programming model. To minimize the total distance travelled by each loaded vehicle, the guide-path sections and their directions were decided by these models. Gaskin and Tanchoco (1987) gave the first model for the AGV flow path design problem using the 0-1 integer programming. Guzman et al. (1997) find out the optimal unidirectional flow path by use of 0-1 programming model with the objective of minimizing the total material flow.

The AGVS guide path configurations discussed in previous research include conventional (Srikanth and Rao, 2011; Banerjee and Barai, 2007; Gaskins and Tanchoco, 1987; Kaspi and Tanchoco, 1990; Venkataraman and Wilson, 1991), tandem (Farahani et al., 2008; Bozer and Srinivasan, 1991; Lin et al., 1994), single-loop (Tanchoco and Sinriech, 1992; Sinriech and Tanchoco, 1993), bi-directional shortest path (Sarker and Gaurav, 2005; Egbelu and Tanchoco, 1986; Gaskins et al., 1989; Kim and Tanchoco, 1991; Chhajed et al., 1992) and the segmental flow topology (SFT) (Sinriech and Tanchoco, 1994).

Srikanth and Rao (2011) discussed the path layout design and a routing algorithm with the objective of minimizing the distance travelled by AGVs. Sarker and Gaurav (2005) discussed the problem of designing of guide path layout and routing algorithm for AGV along the bi-directional path to minimize the total distance travelled. Egbelu and Tanchoco (1986) provided the parameter for designing of the single lane bidirectional guide-path systems. Gaskins et al. (1989) suggested a model for minimizing the vehicle travel distance and the number of lanes using a bidirectional guide-path system. Banerjee and Barai (2007) used 0-1 integer programming for the selection of optimum flow path for AGVs in FMS. The objective was to minimize the total distance travelled by each loaded AGV. Asef-Vaziri et al. (2000) formulate the shortest loop design problem as an integer linear programming model. Venkataramanan and Wilson (1991) used the branch and bound algorithm for unidirectional flow path design. For determining the unidirectional flow path layouts keeping the distance travelled by the vehicles minimum, different heuristics were developed by Kouvelis and Kim (1992). To define the part assignment and tool allocation in FMS with AGVs, an integer programming model was developed by Leung et al. (1993). To formulate AGV routing and dispatching problem, a mixed 0-1 integer programming model was proposed by Krishnamurthy et al. (1993). The model was designed with the objective of minimizing the total travel time in a bi-directional path layout. Goetz and Egbelu (1990) presented a 0-1 integer programming model for identifying the location of pickup/delivery stations based on a finite set of available sites.

Maxwell and Muckstadt (1982) developed a method for determining the minimum number of vehicle required and the vehicle routes to satisfy the required material handling load. Lim et al.

(2002) designed a model to deliberate on the total vehicle travel time, including the empty and loaded vehicle travel time, and time lost caused by congestion and vehicle interference. By utilizing the Q-learning technique, they evaluated the total vehicle travel time. Blair et al. (1985) used the integer programming techniques to discuss the problem of vehicle routing so that the routes of the vehicle could be determined. The objective of their approach was to minimize the maximum distance that a vehicle travels by developing a vehicle routing schedule.

6.3 VARIOUS ASPECTS RELATED TO AGVs

Various aspects related to AGVs are discussed below:

6.3.1 Guidance Technology

- Based on the installation cost, available facilities, future plans for expansion, varying customer demands and the frequency of transportation; various guidance methods can be adopted (Yaghoubi et al., 2012). Some guidance systems can have high reliability, but at the same time, these guidance systems can restrict the flexibility of the organization. Other guidance systems can have slightly less reliability, but if the organization decides to expand or change the layout of an AGV track, then these guidance systems can easily be moved or added to accommodate the changes. Wire guidance, optical guidance, laser guidance and self-guided vehicles are most commonly used guidance systems.

- **Wire guidance:** It is the most widely used type of guidance system. It is reliable but not flexible. A slot is cut into the floor and a wire connected to a frequency generator which emits a low voltage and low current signal with a frequency in the range 1-15 kHz, is placed approximately 1 inch below the surface (Groover, 2008). Due to the current flowing through the electric wire, an electromagnetic field is generated around the wire itself. A sensor is installed on the bottom of the AGV close to the ground. The sensor detects the relative position of the wire through the electromagnetic field because the strength of this field is stronger closer to the wire. This information is used to regulate the steering circuit, making the AGV follow the wire. The different frequency is used to control the steering which makes the required changes in the vehicle direction (Das and Pasan, 2016).

- **Optical guidance:** Two basic types of optical guidance systems used in industries are: spot guidance and painted strip guidance system. In the case of spot guidance, spots of reflective material are used on the ground and lights on the bottom of the vehicle. This light is reflected off by the reflective spot to guide the vehicle. In the case of painted strip guidance system, a paint strip or chemical paths such as fluorescent particles (to reflect an ultraviolet light source from the AGV) or dye are laid on the floor (Groover, 2008). To trace the line drawn on the floor, the AGV uses an on-board sensor which sends the signal to control system of the AGV for controlling the steering mechanism to follow it (Das and Pasan, 2016).

- **Laser guidance:** In this guidance system, reflective targets and laser scanner are used to guide the vehicle. These targets are mounted on the wall and scanned by the scanner on the AGV. The information gathered from the laser scanner is used to guide the vehicle. The laser technique provides extensive flexibility because here, AGVs do not require any pathways, wires or rails and can be easily programmed for both indoor and outdoor driving. The routes can be changed within the software. (Yaghoubi et al., 2012).

- **Self-guided vehicles (SGVs):** It is the latest guidance technology which operates without continuously defined pathways (Das and Pasan, 2016). Here, SGV uses the combination of dead reckoning and beacons located throughout the plant, which can be identified by the on-board sensors (Groover, 2008). The vehicle’s on-board computer analyzes the required number of wheel rotation in a sequence of specified steering angles to accomplish the movement of the vehicle along the route. The analyzed positions are verified by the beacons located throughout the plant.

6.3.2 Vehicle Management

To operate efficiently, to increase the productivity of AGV and to minimize the traffic congestion in the guide path, the vehicle should be properly utilized. In order to minimize the waiting time at loading/unloading stations, the delivery task must be assigned to vehicles (Groover, 2008). To prevent the collision and to minimize the interference between vehicles, traffic management is necessary. Traffic management can be done by using on-board vehicle sensing and zone control as discussed below:

- **On-board vehicle sensing:** The presence of others vehicles and obstacles ahead in the guide path are detected by one or more sensors mounted on each vehicle (Groover, 2008). According to Zeng et al. (1991), AGV stops at its position if the on-board sensor detects that they are too close to other vehicles i.e., the distance between it and the other vehicle in front of it is less than the threshold value. When the vehicle or obstacle present in the guide path is removed, then only AGV proceeds and collision between vehicles is avoided.

- **Zone control:** Zone control is a widely used method for traffic management and to avoid the deadlock situations. Two type of zone control systems are used in industries: static zone control and dynamic zone control. In the case of static zone control, the system guide path is broken into several segments where vehicle collisions are avoided by allowing a single vehicle into a zone at any given time (Malmborg, 1992). If a vehicle is already present in a zone, then the controller gives the signal to the vehicle waiting outside the zone. After getting the signal, the vehicle has to wait until the zone becomes vacant (Le-Anh and De-Koster, 2004). So, by controlling the forward movement of vehicles in separate zones, a collision between vehicles can be avoided. In the case of dynamic zone control, depending on the traffic flow in the system, zones can changed. They are not permanent i.e., give flexibility to change the position and number of zones. To prevent the collisions between vehicles, a dynamic zone strategy was proposed by Ho (2000).

6.3.3 Vehicle Dispatching System

For the efficient working of AGVs, vehicles must be dispatched in an appropriate and efficient way to the locations where they are needed (Groover, 2008). Main objectives of vehicle dispatching systems are minimizing the load waiting time, minimizing the queue length and maximizing the system throughput (Le-Anh and De-Koster, 2004). Most widely used methods in commercial AGV system for dispatching vehicles are: on-board control panel, remote call stations and central computer control as discussed below:

- **On-board control panel:** Each AGV is equipped with the on-board control panel for the purpose of manual vehicle control, vehicle programming and performing other tasks.

With the help of this control panel, vehicles can be dispatched to a given point/stations in AGV layout (Groover, 2008). This dispatching system represents the lowest level of complexity among the possible methods and also provides AGVs with more flexibility and ability to respond quickly to varying requirements on handling system (Narayan et al., 2008).

- **Remote call stations:** In the case of simple remote call station, a press button is provided near each loading/unloading station. This press button gives a signal to any available vehicle in the neighborhood, so that it can approach the station to carry out the task of either pickup or drop off a load, and then with the help of on-board control panel, the vehicle might be dispatched to the desired location (Narayan et al., 2008). In the case of complicated remote call stations, when the vehicle is called up by any station then, at the same time the vehicles destinations may be programmed (Groover, 2008). So, a combination of the on-board control panel and remote call station methods are used for dispatching the vehicles at the desired location on time.

- **Central computer control:** This control system is used to carry out the automatic dispatching of vehicles depending on the pre-planned agenda of pick-ups and deliveries in the layout and/or in response to the calls from the various loading/unloading stations in the system (Narayan et al., 2008). This control system has the flexibility to opt any available AGV which is closest to the station, to carry out the task and then dispatch it automatically (Alavudeen and Venkateshwaran, 2010). It is the highest level of control possible and provides the facility of automatic tracking of each load in the system.

6.3.4 Safety Features in AGVs

Safety of the human personnel present along the pathway is a very important issue of concern during the designing of AGV. A number of features are provided in the AGVs for the safety reasons, some of them are discussed below:

- Due to the slow travelling speed of AGVs, the danger of overtaking a human walking along the guide path in front of the vehicle is minimized (Groover, 2008).
- For the safety purpose, an obstacle-detection sensor is mounted at the front of each vehicle to sense not only the presence of other vehicles but also human beings and other

obstacles in the path of the vehicle (Narayan et al., 2008). The vehicles are programmed either to stop or to slow down when an obstacle is sensed ahead of it.

- Another device for safety purpose is an emergency bumper surrounding the front of the vehicles which is mounted on almost all commercial AGVs. When this bumper makes contact with people or other obstacles, the resulting impact activate the vehicle emergency brake and simultaneously cut the power to the driving motors (Parsaei and Mital, 2012).
- Other devices provided on the AGVs for the safety purpose are warning lights (blinking or rotating lights) and/or warning alarms to alert human beings located along the route of the vehicles. The warning lights or alarms notify the people to move the obstacles present in the guide path so that AGV could proceed to its destination (Parsaei and Mital, 2012).

6.4 IDENTIFICATION OF FACTORS AFFECTING THE DESIGN AND DEVELOPMENT OF AGVs

The design of MHS using AGVs depends on various factors as discussed by many authors. These factors are shown in Table 6.1. These factors are divided into two categories, one based on the literature review and the other on the basis of experts' opinion, both from the academia and industry.

Table 6.1: Factors affecting the design and development of AGVs

S.No.	Factors	References/Resources
1	AGVs path layout	Sharma (2012); Malmborg (1990); Koff (1987)
2	Volume of production	Vis (2006)
3	Traffic management technique	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Mahadevan and Narendran (1990); Malmborg (1990);
4	Layouts of AGV tracks in the industry	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Mahadevan and Narendran (1990); Malmborg (1990); Koff (1987)

S.No.	Factors	References/Resources
5	Economic condition of the industry	Expert opinion
6	Organization culture	Expert opinion
7	Maintenance requirements of AGV	Expert opinion
8	Information management system	Expert opinion
9	Process sequence of the manufacturing system	Expert opinion
10	Positioning of idle vehicles	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Mahadevan and Narendran (1990); Malmborg (1990); Koff (1987)
11	Communication system	Sharma (2012)
12	Facility layout	Mantel and Landeweerd (1995)
13	Battery management	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Mahadevan and Narendran (1990); Malmborg (1990); Koff (1987)
14	Procurement of AGV's	Sharma (2012); Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Mahadevan and Narendran (1990); Malmborg (1990); Koff (1987)
15	Failure management	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Mahadevan and Narendran (1990); Malmborg (1990); Koff (1987)
16	Management of control zone	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Hsieh and Lin (1991); Mahadevan and Narendran (1990)

S.No.	Factors	References/Resources
17	Speed of AGV’s	Vis (2006); Banerjee and Bhattacharya (2005)
18	Proper training	Expert opinion
19	Buffer capacity of each vehicle	Sharma (2012); Raj et al. (2007a); Vis (2006); Mantel and Landeweerd (1995); Mahadevan and Narendran, (1990)

The flow path is the fixed guide paths on which the vehicle can travel to the various pick-up and delivery points of loads. To avoid the collisions and deadlock situations, traffic management is required. To prevent from physical collisions and obstacles in the path, sensors are attached on the AGVs. Xu et al. (2003) discussed the concepts for obstacle avoidance. Zone control is the most popular and widely used type of traffic management technique. Vehicle travel from one zone to another and only one vehicle is allowed at one time in a zone.

The location of pickup and delivery points influences the operational performance, so the choice of the location of these points is important. According to Maxwell and Muckstadt (1982), Goetz and Egbelu (1990) and Asef-Vaziri et al. (2000), the choice of location can be decided during the design of the system. After delivering the job at its destination, if AGV is not assigned to a new job, then it becomes idle. AGV should respond as quickly as possible to a new job to reduce the waiting time of loads for transport. Therefore, the location of the idle vehicle should be chosen carefully. Egbelu (1993) studied the problem of positioning an idle AGV in a loop layout. He discussed, how to determine the locations for idle vehicles in both unidirectional and bidirectional loop layouts by minimizing the maximum response time.

Battery management of AGVs is important to reduce costs and improve the efficiency of the AGV. Valve regulated lead-acid (VRLA) are used in AGVs due to their high reliability and low cost. The life of the batteries varies depending on their operation mode, its usage such as the timing of charge. Thus to avoid battery deterioration (insufficient charging, over discharge) and consequently reduce battery related costs, it is important to manage the timing of charge. Failure management of the equipment is also an important factor because it might cause congestion and deadlocks in the system. Control methods to deal with failures of full and empty AGVs in underground transportation system are developed by Ebben (2001). Sufficient number of AGVs with good speed should be available to transport the load at the right time. The number of round-trips that each vehicle makes per hour and the total number of round trips can be used to estimate the total number of vehicles required (Ilic, 1994).

6.5 FLOW PATH DETERMINATION

The objective of the mathematical programming problem is to determine the direction of each arc in an unidirectional flow path network such that the total travel distance of loaded vehicles is minimized. In the present research, the layout for AGVS operating through 4 manufacturing cells has been designed, and 0-1 linear integer programming approach has been used to solve the problem.

The informations that must be obtained before the formulation of the problem are: a layout of manufacturing cells, aisles, pick-up (P) and delivery (D) stations, the location of these P/D stations and a from-to chart containing the material flow intensities of loaded vehicles between different cells. After determining the above information, next step is to convert this information into the node-arc network. Nodes represent the pick-up points, delivery points, path intersections, corners and the arc represent the direction of flow between two adjacent nodes. Every node is assigned a number, and an arc is identified by a variable $A_{ij.}$

6.5.1 Layout Description and Formulation of the Problem

Manufacturing cells layout is shown in Figure 6.1. This manufacturing facility consists of four cells. The corresponding node and arc diagram is shown in Figure 6.2. The material flow intensity between departments in shown is Table 6.2. P_i is the location of pick-up station, and D_i is the location of the delivery station. For the ease of computation, only one pick-up and delivery point have been taken for each cell, and in some cells, pick-up and the delivery point has been taken at the same point. From the node and arc diagram, it is clear that layout consists of 16 nodes and 19 arcs.

Most of the authors have solved the AGV path layout problem with 0-1 linear integer programming with very complex path layouts. But in the present problem, 0-1 linear integer programming has been used with a very simple example for conceptual clarification and real-time implementation in FMS environment. The case presented here consists of only four cells, it is not typical of a real-world manufacturing cells layout. Normally, AGVs are used in a layout which consists of several cells, and flow exists between several sets of stations. The procedure described in this chapter can be easily extended to more typical and more complex layouts. Whenever number of machine tools and workstations increase in FMS and the AGV path layout becomes very complex, in such cases 0-1 linear integer programming can be used with high-end software, for example, Lingo 14 and shortest path to be followed by AGVs in real time demand for workstations can be found with the use of computer controlled algorithms. The major difference between the present case and complex layouts is in the formulation of the objective function. For each entry, an expression similar to the objective function of the present layout is developed. The sum of these expressions is the objective function for the complex layouts.

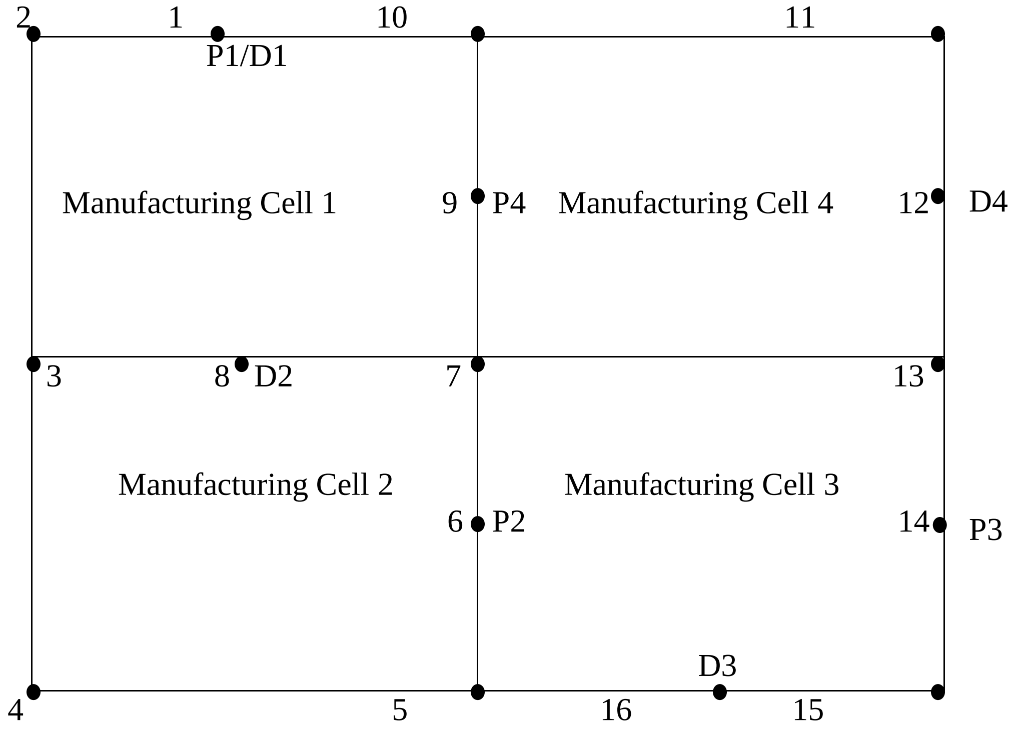


Figure 6.1: Manufacturing Cells Layout

To develop the objective function for the above example, the main criteria is to find the unidirectional flow path to minimize the total loaded travel distance. For this reason, first the available alternatives are found, and then the paths of minimum distance are selected.

Table 6.2: From to Chart of Material Flow Representation $F_{m,n}$ Values

To / From	Cell 1	Cell 2	Cell 3	Cell 4
Cell 1	0	80	60	70
Cell 2	70	0	70	80
Cell 3	100	80	0	80
Cell 4	70	60	70	0

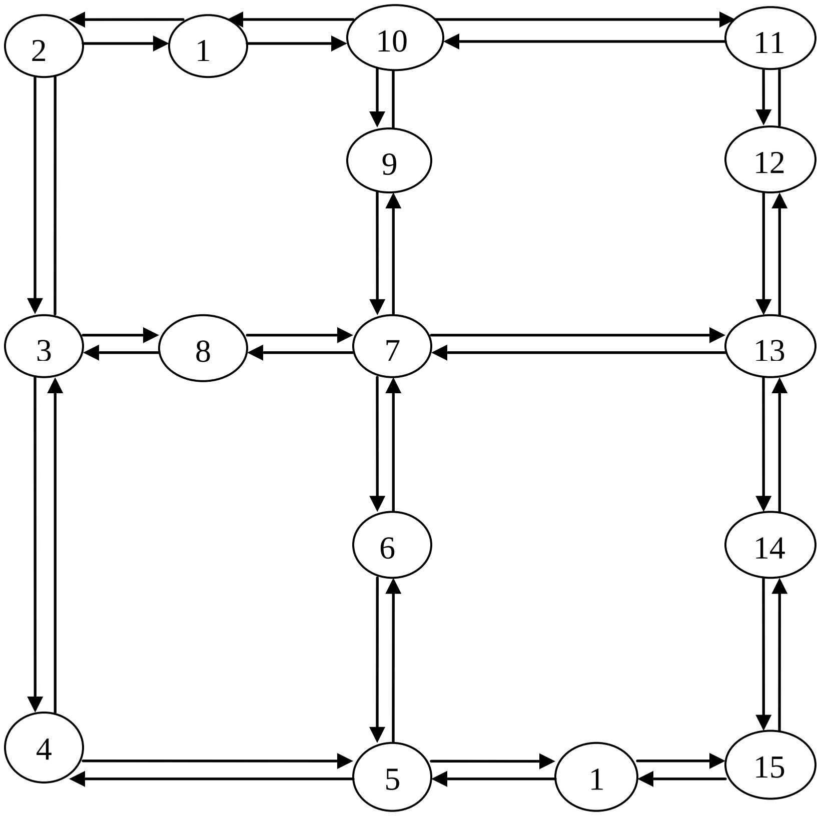


Figure 6.2: Network and arc diagram

When the material flows from cell 1 to cell 2, then it can leave the pick-up point P_1 in two ways, either $A_{1,2}$ or $A_{1,10}$ and correspondingly it can enter the drop-off location in two ways which are either $A_{3,8}$ or $A_{7,8}$. Because unidirectionality is assumed, there are only four distinct possibilities which are $A_{1,2}$ and $A_{3,8}$ or $A_{1,2}$ and $A_{7,8}$ or $A_{1,10}$ and $A_{3,8}$ or $A_{1,10}$ and $A_{7,8}$. For each of the path, there is a shortest path. For the above four combinations, the lengths of the shortest paths are given as 20, 50, 50 and 20 respectively. With these distances, along with the flow intensity, the objective function can be stated as follows:

Min T= $80(20A_{1,2}A_{3,8}+50A_{1,2}A_{7,8}+50A_{1,10}A_{3,8}+20A_{1,10}A_{7,8})$

As variables are zero-one variables, only one of the four combinations can be chosen, and only product of the chosen combination will have the value of 1. All other combinations will have a product of zero. It means only one of the product term from the above objective function $A_{1,2}A_{3,8}$ or $A_{1,2}A_{7,8}$ or $A_{1,10}A_{3,8}$ or $A_{1,10}A_{7,8}$ will have the value 1 and other terms will become 0.

Similarly, when material flows from Cell 1 to Cell 3, Cell 1 to Cell 4, Cell 2 to Cell 1, Cell 2 to Cell 3, Cell 2 to Cell 4, Cell 3 to Cell 1, Cell 3 to Cell 2, Cell 3 to Cell 4, Cell 4 to Cell 1, Cell 4 to Cell 2 and Cell 4 to Cell 3 the corresponding objective functions are obtained. All these objective functions are summed up to get the overall objective function.

When material flows from Cell 1 to Cell 3, then the objective function becomes:

Min T = $60(40A_{1,2}A_{5,16}+50A_{1,2}A_{15,16}+30A_{1,10}A_{5,16}+40A_{1,10}A_{15,16})$

When material flows from Cell 1 to Cell 4, then the objective function becomes:

Min T = $70(50A_{1,2}A_{11,12}+40A_{1,2}A_{13,12}+20A_{1,10}A_{11,12}+30A_{1,10}A_{13,12})$

When material flows from Cell 2 to Cell 1, then the objective function becomes:

Min T = $70(30A_{6,7}A_{2,1}+20A_{6,7}A_{10,1}+40A_{6,5}A_{2,1}+50A_{6,5}A_{10,1})$

When material flows from Cell 2 to Cell 3, then the objective function becomes:

Min T = $70(40A_{6,7}A_{5,16}+30A_{6,7}A_{15,16}+10A_{6,5}A_{5,16}+30A_{6,5}A_{15,16})$

When material flows from Cell 2 to Cell 4, then the objective function becomes:

Min T = $80(30A_{6,7}A_{11,12}+20A_{6,7}A_{13,12}+60A_{6,5}A_{11,12}+30A_{6,5}A_{13,12})$

When material flows from Cell 3 to Cell 1, then the objective function becomes:

Min T = $100(30A_{14,13}A_{10,1}+40A_{14,13}A_{2,1}+40A_{14,15}A_{10,1}+50A_{14,15}A_{2,1})$

When material flows from Cell 3 to Cell 2, then the objective function becomes:

Min T = $80(20A_{14,13}A_{7,8}+50A_{14,13}A_{3,8}+30A_{14,15}A_{7,8}+40A_{14,15}A_{3,8})$

When material flows from Cell 3 to Cell 4, then the objective function becomes:

$\text{Min } T = 80(40A_{14,13}A_{11,12}+10A_{14,13}A_{13,12}+50A_{14,15}A_{11,12}+40A_{14,15}A_{13,12})$

When material flows from Cell 4 to Cell 1, then the objective function becomes:

$\text{Min } T = 70(40A_{9,10}A_{2,1}+10A_{9,10}A_{10,1}+50A_{9,7}A_{2,1}+40A_{9,7}A_{10,1})$

When material flows from Cell 4 to Cell 2, then the objective function becomes:

$\text{Min } T = 60(30A_{9,10}A_{3,8}+20A_{9,10}A_{7,8}+60A_{9,7}A_{3,8}+30A_{9,7}A_{7,8})$

When material flows from Cell 4 to Cell 3, then the objective function becomes:

$\text{Min } T = 70(30A_{9,10}A_{5,16}+40A_{9,10}A_{15,16}+40A_{9,7}A_{5,16}+30A_{9,7}A_{15,16})$

The overall objective function becomes:

$$\text{MinT}=80(20A_{1,2}A_{3,8}+50A_{1,2}A_{7,8}+50A_{1,10}A_{3,8}+20A_{1,10}A_{7,8})+60(40A_{1,2}A_{5,16}+50A_{1,2}A_{15,16}+30A_{1,10}A_{5,16}+40A_{1,10}A_{15,16})+70(50A_{1,2}A_{11,12}+40A_{1,2}A_{13,12}+20A_{1,10}A_{11,12}+30A_{1,10}A_{13,12})+70(30A_{6,7}A_{2,1}+20A_{6,7}A_{10,1}+40A_{6,5}A_{2,1}+50A_{6,5}A_{10,1})+70(40A_{6,7}A_{5,16}+30A_{6,7}A_{15,16}+10A_{6,5}A_{5,16}+30A_{6,5}A_{15,16})+80(30A_{6,7}A_{11,12}+20A_{6,7}A_{13,12}+60A_{6,5}A_{11,12}+30A_{6,5}A_{13,12})+100(30A_{14,13}A_{10,1}+40A_{14,13}A_{2,1}+40A_{14,15}A_{10,1}+50A_{14,15}A_{2,1})+80(20A_{14,13}A_{7,8}+50A_{14,13}A_{3,8}+30A_{14,15}A_{7,8}+40A_{14,15}A_{3,8})+80(40A_{14,13}A_{11,12}+10A_{14,13}A_{13,12}+50A_{14,15}A_{11,12}+40A_{14,15}A_{13,12})+70(40A_{9,10}A_{2,1}+10A_{9,10}A_{10,1}+50A_{9,7}A_{2,1}+40A_{9,7}A_{10,1})+60(30A_{9,10}A_{3,8}+20A_{9,10}A_{7,8}+60A_{9,7}A_{3,8}+30A_{9,7}A_{7,8})+70(30A_{9,10}A_{5,16}+40A_{9,10}A_{15,16}+40A_{9,7}A_{5,16}+30A_{9,7}A_{15,16});$$

Constraint equations to convert non-linearity into linearity:

1. When material moves from Cell 1 to Cell 2, the equations are:
   $A_{1,2}+A_{3,8}-A_{1,2,3,8}\leq 1$; $-A_{1,2}-A_{3,8}+2*A_{1,2,3,8}\leq 0$;
   $A_{1,2}+A_{7,8}-A_{1,2,7,8}\leq 1$; $-A_{1,2}-A_{7,8}+2*A_{1,2,7,8}\leq 0$;
   $A_{1,10}+A_{3,8}-A_{1,10,3,8}\leq 1$; $-A_{1,10}-A_{3,8}+2*A_{1,10,3,8}\leq 0$;
   $A_{1,10}+A_{7,8}-A_{1,10,7,8}\leq 1$; $-A_{1,10}-A_{7,8}+2*A_{1,10,7,8}\leq 0$;
2. When material moves from Cell 1 to Cell 3, the equations are:
   $A_{1,2}+A_{5,16}-A_{1,2,5,16}\leq 1$; $-A_{1,2}-A_{5,16}+2*A_{1,2,9,5,16}\leq 0$;
   $A_{1,2}+A_{15,16}-A_{1,2,15,16}\leq 1$; $-A_{1,2}-A_{15,16}+2*A_{1,2,15,16}\leq 0$;
   $A_{1,10}+A_{5,16}-A_{1,10,5,16}\leq 1$; $-A_{1,10}-A_{5,16}+2*A_{1,10,5,16}\leq 0$;

$A_{1,10}+A_{15,16}-A_{1,10,15,16}\leq 1$; $-A_{1,10}-A_{15,16}+2*A_{1,10,15,16}\leq 0$;

3. When material moves from Cell 1 to Cell 4, the equations are:

   $A_{1,2}+A_{11,12}-A_{1,2,11,12}\leq 1$; $-A_{1,2}-A_{11,12}+2*A_{1,2,11,12}\leq 0$;

   $A_{1,2}+A_{13,12}-A_{1,2,13,12}\leq 1$; $-A_{1,2}-A_{13,12}+2*A_{1,2,13,12}\leq 0$;

   $A_{1,10}+A_{11,12}-A_{1,10,11,12}\leq 1$; $-A_{1,10}-A_{11,12}+2*A_{1,10,11,12}\leq 0$;

   $A_{1,10}+A_{13,12}-A_{1,6,13,12}\leq 1$; $-A_{1,10}-A_{13,12}+2*A_{1,10,13,12}\leq 0$;

4. When material moves from Cell 2 to Cell 1, the equations are:

   $A_{6,7}+A_{10,1}-A_{6,7,10,1}\leq 1$; $-A_{6,7}-A_{10,1}+2*A_{6,7,10,1}\leq 0$;

   $A_{6,7}+A_{2,1}-A_{6,7,2,1}\leq 1$; $-A_{6,7}-A_{2,1}+2*A_{6,7,2,1}\leq 0$;

   $A_{6,5}+A_{2,1}-A_{6,5,2,1}\leq 1$; $-A_{6,5}-A_{2,1}+2*A_{6,5,2,1}\leq 0$;

   $A_{6,5}+A_{10,1}-A_{6,5,10,1}\leq 1$; $-A_{6,5}-A_{10,1}+2*A_{6,5,10,1}\leq 0$;

5. When material moves from Cell 2 to Cell 3, the equations are:

   $A_{6,7}+A_{5,16}-A_{6,7,5,16}\leq 1$; $-A_{6,7}-A_{5,16}+2*A_{6,7,5,16}\leq 0$;

   $A_{6,7}+A_{15,16}-A_{6,7,15,16}\leq 1$; $-A_{6,7}-A_{15,16}+2*A_{6,7,15,16}\leq 0$;

   $A_{6,5}+A_{5,16}-A_{6,5,5,16}\leq 1$; $-A_{6,5}-A_{5,16}+2*A_{6,5,5,16}\leq 0$;

   $A_{6,5}+A_{15,16}-A_{6,5,15,16}\leq 1$; $-A_{6,5}-A_{15,16}+2*A_{6,5,15,16}\leq 0$;

6. When material moves from Cell 2 to Cell 4, the equations are:

   $A_{6,5}+A_{11,12}-A_{6,5,11,12}\leq 1$; $-A_{6,5}-A_{11,12}+2*A_{6,5,11,12}\leq 0$;

   $A_{6,5}+A_{13,12}-A_{6,5,13,12}\leq 1$; $-A_{6,5}-A_{13,12}+2*A_{6,5,13,12}\leq 0$;

   $A_{6,7}+A_{11,12}-A_{6,7,11,12}\leq 1$; $-A_{6,7}-A_{11,12}+2*A_{6,7,11,12}\leq 0$;

   $A_{6,7}+A_{13,12}-A_{6,7,13,12}\leq 1$; $-A_{6,7}-A_{13,12}+2*A_{6,7,13,12}\leq 0$;

7. When material moves from Cell 3 to Cell 1, the equations are:

   $A_{14,15}+A_{10,1}-A_{14,15,10,1}\leq 1$; $-A_{14,15}-A_{10,1}+2*A_{14,15,10,1}\leq 0$;

   $A_{14,15}+A_{2,1}-A_{14,15,2,1}\leq 1$; $-A_{14,15}-A_{2,1}+2*A_{14,15,2,1}\leq 0$;

   $A_{14,13}+A_{10,1}-A_{14,13,10,1}\leq 1$; $-A_{14,13}-A_{10,1}+2*A_{14,13,10,1}\leq 0$;

   $A_{14,13}+A_{2,1}-A_{14,13,2,1}\leq 1$; $-A_{14,13}-A_{2,1}+2*A_{14,13,2,1}\leq 0$;

8. When material moves from Cell 3 to Cell 2, the equations are:

   $A_{14,15}+A_{7,8}-A_{14,15,7,8}\leq 1$; $-A_{14,15}-A_{7,8}+2*A_{14,15,7,8}\leq 0$;

   $A_{14,15}+A_{3,8}-A_{14,15,3,8}\leq 1$; $-A_{14,15}-A_{3,8}+2*A_{14,15,3,8}\leq 0$;

$A_{14,13}+A_{7,8}-A_{14,13,7,8}\leq 1$; $-A_{14,13}-A_{7,8}+2*A_{14,13,7,8}\leq 0$;

$A_{14,13}+A_{3,8}-A_{14,13,3,8}\leq 1$; $-A_{14,13}-A_{3,8}+2*A_{14,13,3,8}\leq 0$;

9. When material moves from Cell 3 to Cell 4, the equations are:

   $A_{14,15}+A_{11,12}-A_{14,15,11,12}\leq 1$; $-A_{14,15}-A_{11,12}+2*A_{14,15,11,12}\leq 0$;

   $A_{14,15}+A_{13,12}-A_{14,15,13,12}\leq 1$; $-A_{14,15}-A_{13,12}+2*A_{14,15,13,12}\leq 0$;

   $A_{14,13}+A_{11,12}-A_{14,13,11,12}\leq 1$; $-A_{14,13}-A_{11,12}+2*A_{14,13,11,12}\leq 0$;

   $A_{14,13}+A_{13,12}-A_{14,13,13,12}\leq 1$; $-A_{14,13}-A_{13,12}+2*A_{14,13,13,12}\leq 0$;

10. When material moves from Cell 4 to Cell 1, the equations are

    $A_{9,10}+A_{2,1}-A_{9,10,2,1}\leq 1$; $-A_{9,10}-A_{2,1}+2*A_{9,10,2,1}\leq 0$;

    $A_{9,10}+A_{10,1}-A_{9,10,10,1}\leq 1$; $-A_{9,10}-A_{10,1}+2*A_{9,10,10,1}\leq 0$;

    $A_{9,7}+A_{2,1}-A_{9,7,2,1}\leq 1$; $-A_{9,7}-A_{2,1}+2*A_{9,7,2,1}\leq 0$;

    $A_{9,7}+A_{10,1}-A_{9,7,10,1}\leq 1$; $-A_{9,7}-A_{10,1}+2*A_{9,7,10,1}\leq 0$;

11. When material moves from Cell 4 to Cell 2, the equations are:

    $A_{9,10}+A_{3,8}-A_{9,10,3,8}\leq 1$; $-A_{9,10}-A_{3,8}+2*A_{9,10,3,8}\leq 0$;

    $A_{9,10}+A_{7,8}-A_{9,10,7,8}\leq 1$; $-A_{9,10}-A_{7,8}+2*A_{9,10,7,8}\leq 0$;

    $A_{9,7}+A_{3,8}-A_{9,7,3,8}\leq 1$; $-A_{9,7}-A_{3,8}+2*A_{9,7,3,8}\leq 0$;

    $A_{9,7}+A_{7,8}-A_{9,7,7,8}\leq 1$; $-A_{9,7}-A_{7,8}+2*A_{9,7,7,8}\leq 0$;

12. When material moves from Cell 4 to Cell 3, the equations are:

    $A_{9,10}+A_{5,16}-A_{9,10,5,16}\leq 1$; $-A_{9,10}-A_{5,16}+2*A_{9,10,5,16}\leq 0$;

    $A_{9,10}+A_{15,16}-A_{9,10,15,16}\leq 1$; $-A_{9,10}-A_{15,16}+2*A_{9,10,15,16}\leq 0$;

    $A_{9,7}+A_{5,16}-A_{9,7,5,16}\leq 1$; $-A_{9,7}-A_{5,16}+2*A_{9,7,5,16}\leq 0$;

    $A_{9,7}+A_{15,16}-A_{9,7,15,16}\leq 1$; $-A_{9,7}-A_{15,16}+2*A_{9,7,15,16}\leq 0$;

Constraints to ensure unidirectional network

$A_{1,2}+A_{2,1}=1$; $A_{2,3}+A_{3,2}=1$;

$A_{3,8}+A_{8,3}=1$; $A_{3,4}+A_{4,3}=1$;

$A_{4,5}+A_{5,4}=1$; $A_{8,7}+A_{7,8}=1$;

$A_{5,6}+A_{6,5}=1$; $A_{9,7}+A_{7,9}=1$;

$A_{7,6}+A_{6,7}=1$; $A_{9,10}+A_{10,9}=1$;

$A_{1,10}+A_{10,1}=1$; $A_{11,10}+A_{10,11}=1$;

$A_{12,13}+A_{13,12}=1$; $A_{13,14}+A_{14,13}=1$;

$A_{14,15}+A_{15,14}=1$; $A_{15,16}+A_{16,15}=1$;

$A_{16,5}+A_{5,16}=1$; $A_{7,13}+A_{13,7}=1$;

$A_{11,12}+A_{12,11}=1$;

Constraints to ensure at least one input arc to each node

$A_{1,2}+A_{3,2} \geq 1$; $A_{2,3}+A_{4,3}+A_{8,3} \geq 1$;

$A_{3,4}+A_{5,4} \geq 1$; $A_{4,5}+A_{6,5}+A_{16,5} \geq 1$;

$A_{9,10}+A_{1,10}+A_{11,10} \geq 1$; $A_{5,16}+A_{15,16} \geq 1$;

$A_{5,6}+A_{7,6} \geq 1$; $A_{3,8}+A_{7,8} \geq 1$;

$A_{14,13}+A_{12,13}+A_{7,13} \geq 1$; $A_{13,14}+A_{15,14} \geq 1$;

$A_{7,9}+A_{10,9} \geq 1$; $A_{2,1}+A_{10,1} \geq 1$;

$A_{13,12}+A_{11,12} \geq 1$; $A_{10,11}+A_{12,11} \geq 1$;

$A_{8,7}+A_{6,7}+A_{13,7}+A_{9,7} \geq 1$; $A_{14,15}+A_{16,15} \geq 1$;

Constraints to ensure at least one output arc to each node

$A_{2,1}+A_{2,3} \geq 1$; $A_{3,2}+A_{3,4}+A_{3,8} \geq 1$;

$A_{4,3}+A_{4,5} \geq 1$; $A_{5,4}+A_{5,6}+A_{5,16} \geq 1$;

$A_{6,5}+A_{6,7} \geq 1$; $A_{8,3}+A_{8,7} \geq 1$;

$A_{9,7}+A_{9,10} \geq 1$; $A_{10,9}+A_{10,1}+A_{10,11} \geq 1$;

$A_{13,14}+A_{13,12}+A_{13,7} \geq 1$; $A_{12,13}+A_{12,11} \geq 1$;

$A_{1,2}+A_{1,10} \geq 1$; $A_{11,12}+A_{11,10} \geq 1$;

$A_{14,13}+A_{14,15} \geq 1$; $A_{15,14}+A_{15,16} \geq 1$;

$A_{7,8}+A_{7,6}+A_{7,13}+A_{7,9} \geq 1$; $A_{16,15}+A_{16,5} \geq 1$;

Constraint for a node, which is intersection of four arcs

$A_{8,7}+A_{6,7}+A_{13,7}+A_{9,7} \geq 2$;

Constraints to prevent a group of nodes from becoming sink nodes

$A_{1,10}+A_{2,3}=1$; $A_{10,1}+A_{3,2}=1$;

$A_{13,14}+A_{5,16}=1$; $A_{14,13}+A_{16,5}=1$;

Constraints to ensure inclusion of intermediate arcs in a particular path

1. When material moves from Cell 1 to Cell 2, the equations are:

   $A_{1,2}+A_{3,8}-A_{2,3}-1<=0;$

   $5*A_{1,2}+5*A_{7,8}-A_{2,3}-A_{3,4}-A_{4,5}-A_{5,6}-A_{6,7}-5<=0;$

   $6*A_{1,10}+6*A_{3,8}-A_{10,9}-A_{9,7}-A_{7,6}-A_{6,5}-A_{5,4}-A_{4,3}-6<=0;$

   $2*A_{1,10}+2*A_{7,8}-A_{10,9}-A_{9,7}-2<=0;$

2. When material moves from Cell 1 to Cell 3, the equations are:

   $3*A_{1,2}+3*A_{5,16}-A_{2,3}-A_{3,4}-A_{4,5}-3<=0;$

   $6*A_{1,2}+6*A_{15,16}-A_{2,3}-A_{3,8}-A_{8,7}-A_{7,13}-A_{13,14}-A_{14,15}-6<=0;$

   $4*A_{1,10}+4*A_{5,16}-A_{10,9}-A_{9,7}-A_{7,6}-A_{6,5}-4<=0;$

   $5*A_{1,10}+5*A_{15,16}-A_{10,9}-A_{9,7}-A_{7,13}-A_{13,14}-A_{14,15}-5<=0;$

3. When material moves from Cell 1 to Cell 4, the equations are:

   $3*A_{1,10}+3*A_{13,12}-A_{10,9}-A_{9,7}-A_{7,13}-3<=0;$

   $A_{1,10}+A_{11,12}-A_{10,11}-1<=0;$

   $4*A_{1,2}+4*A_{13,12}-A_{2,3}-A_{3,8}-A_{8,7}-A_{7,13}-4<=0;$

   $6*A_{1,2}+6*A_{11,12}-A_{2,3}-A_{3,8}-A_{8,7}-A_{7,9}-A_{9,10}-A_{10,11}-6<=0;$

4. When material moves from Cell 2 to Cell 1, the equations are:

   $6*A_{6,5}+6*A_{10,1}-A_{5,4}-A_{4,3}-A_{3,8}-A_{8,7}-A_{7,9}-A_{9,10}-6<=0;$

   $3*A_{6,5}+3*A_{2,1}-A_{5,4}-A_{4,3}-A_{3,2}-3<=0;$

   $3*A_{6,7}+3*A_{2,1}-A_{7,8}-A_{8,3}-A_{3,2}-3<=0;$

   $2*A_{6,7}+2*A_{10,1}-A_{7,9}-A_{9,10}-2<=0;$

5. When material moves from Cell 2 to Cell 3, the equations are:

   $4*A_{6,7}+4*A_{5,16}-A_{7,8}-A_{8,3}-A_{3,4}-A_{4,5}-4<=0;$

   $3*A_{6,7}+3*A_{15,16}-A_{7,13}-A_{13,14}-A_{14,15}-3<=0;$

   $7*A_{6,5}+7*A_{15,16}-A_{5,4}-A_{4,3}-A_{3,8}-A_{8,7}-A_{7,13}-A_{13,14}-A_{14,15}-7<=0;$

6. When material moves from Cell 2 to Cell 4, the equations are:

   $A_{6,7}+A_{13,12}-A_{7,13}-1<=0;$

   $3*A_{6,7}+3*A_{11,12}-A_{7,9}-A_{9,10}-A_{10,11}-3<=0;$

   $4*A_{6,5}+4*A_{13,12}-A_{5,16}-A_{16,15}-A_{15,14}-A_{14,13}-4<=0;$

$7*A_{6,5}+7*A_{11,12}-A_{5,4}-A_{4,3}-A_{3,8}-A_{8,7}-A_{7,9}-A_{9,10}-A_{10,11}-7<=0;$

7. When material moves from Cell 3 to Cell 1, the equations are:

   $4*A_{14,13}+4*A_{2,1}-A_{13,7}-A_{7,8}-A_{8,3}-A_{3,2}-4<=0;$

   $3*A_{14,13}+3*A_{10,1}-A_{13,7}-A_{7,9}-A_{9,10}-3<=0;$

   $5*A_{14,15}+5*A_{2,1}-A_{15,16}-A_{16,5}-A_{5,4}-A_{4,3}-A_{3,2}-5<=0;$

   $6*A_{14,15}+6*A_{10,1}-A_{15,16}-A_{16,5}-A_{5,6}-A_{6,7}-A_{7,9}-A_{9,10}-6<=0;$

8. When material moves from Cell 3 to Cell 2, the equations are:

   $4*A_{14,15}+4*A_{3,8}-A_{15,16}-A_{16,5}-A_{5,4}-A_{4,3}-4<=0;$

   $4*A_{14,15}+4*A_{7,8}-A_{15,16}-A_{16,5}-A_{5,6}-A_{6,7}-4<=0;$

   $5*A_{14,13}+5*A_{3,8}-A_{13,7}-A_{7,6}-A_{6,5}-A_{5,4}-A_{4,3}-5<=0;$

   $A_{14,13}+A_{7,8}-A_{13,7}-1<=0;$

9. When material moves from Cell 3 to Cell 4, the equations are:

   $7*A_{14,15}+7*A_{11,12}-A_{15,16}-A_{16,5}-A_{5,6}-A_{6,7}-A_{7,9}-A_{9,10}-A_{10,11}-7<=0;$

   $5*A_{14,15}+5*A_{13,12}-A_{15,16}-A_{16,5}-A_{5,6}-A_{6,7}-A_{7,13}-5<=0;$

   $4*A_{14,13}+4*A_{11,12}-A_{13,7}-A_{7,9}-A_{9,10}-A_{10,11}-4<=0;$

10. When material moves from Cell 4 to Cell 1, the equations are:

    $7*A_{9,10}+7*A_{2,1}-A_{10,11}-A_{11,12}-A_{12,13}-A_{13,7}-A_{7,8}-A_{8,3}-A_{3,2}-7<=0;$

    $3*A_{9,7}+3*A_{2,1}-A_{7,8}-A_{8,3}-A_{3,2}-3<=0;$

    $4*A_{9,7}+4*A_{10,1}-A_{7,13}-A_{13,12}-A_{12,11}-A_{11,10}-4<=0;$

11. When material moves from Cell 4 to Cell 2, the equations are:

    $4*A_{9,10}+4*A_{7,8}-A_{10,11}-A_{11,12}-A_{12,13}-A_{13,7}-4<=0;$

    $3*A_{9,10}+3*A_{3,8}-A_{10,1}-A_{1,2}-A_{2,3}-3<=0;$

    $4*A_{9,7}+4*A_{3,8}-A_{7,6}-A_{6,5}-A_{5,4}-A_{4,3}-4<=0;$

12. When material moves from Cell 4 to Cell 3, the equations are:

    $5*A_{9,10}+5*A_{15,16}-A_{10,11}-A_{11,12}-A_{12,13}-A_{13,14}-A_{14,15}-5<=0;$

    $5*A_{9,10}+5*A_{15,16}-A_{10,1}-A_{1,2}-A_{2,3}-A_{3,4}-A_{4,5}-5<=0;$

    $3*A_{9,7}+3*A_{15,16}-A_{7,13}-A_{13,14}-A_{14,15}-3<=0;$

    $2*A_{9,7}+2*A_{5,16}-A_{7,6}-A_{6,5}-2<=0;$

To ensure that the variables should have binary values (0 or 1) only, the following statements are needed in the program:

Bin $A_{1,2}$; Bin $A_{2,1}$; Bin $A_{2,3}$; Bin $A_{3,2}$;
Bin $A_{3,4}$; Bin $A_{4,3}$; Bin $A_{4,5}$; Bin $A_{5,4}$;
Bin $A_{5,6}$; Bin $A_{6,5}$; Bin $A_{5,16}$; Bin $A_{16,5}$;
Bin $A_{6,7}$; Bin $A_{7,6}$; Bin $A_{7,8}$; Bin $A_{8,7}$;
Bin $A_{8,3}$; Bin $A_{3,8}$; Bin $A_{9,7}$; Bin $A_{7,9}$;
Bin $A_{9,10}$; Bin $A_{10,9}$; Bin $A_{10,1}$; Bin $A_{1,10}$;
Bin $A_{10,11}$; Bin $A_{11,10}$; Bin $A_{11,12}$; Bin $A_{12,11}$;
Bin $A_{12,13}$; Bin $A_{13,12}$; Bin $A_{13,14}$; Bin $A_{14,13}$;
Bin $A_{13,7}$; Bin $A_{7,13}$; Bin $A_{14,15}$; Bin $A_{15,14}$;
Bin $A_{15,16}$; Bin $A_{16,15}$;

6.6 RESULT AND DISCUSSION

With the help of LINGO 14 Software package, the above problem was solved as a 0-1 linear integer programming, then the path for the manufacturing cells was obtained. LINGO is an inclusive tool designed to solve mathematical optimization models in simpler and more efficient way. To draw the optimal flow path layout (OFPL), the variables and paths, which are important, are shown below with values collected from the solution. These variables and paths are:

$A_{1,10} = 1$
$A_{2,1} = 1$
$A_{3,2} = 1$
$A_{4,3} = 1$
$A_{5,4} = 1$
$A_{5,6} = 1$
$A_{6,7} = 1$
$A_{7,8} = 1$
$A_{7,13} = 1$
$A_{8,3} = 1$
$A_{9,7} = 1$
$A_{10,9} = 1$

$A_{11,10} = 1$
$A_{12,11} = 1$
$A_{13,12} = 1$
$A_{13,14} = 1$
$A_{14,15} = 1$
$A_{15,16} = 1$
$A_{16,5} = 1$

$A_{1,10,7,8} = 1$
$A_{1,10,15,16} = 1$
$A_{1,10,13,12} = 1$
$A_{6,7,2,1} = 1$
$A_{6,7,15,16} = 1$
$A_{6,7,13,12} = 1$
$A_{14,15,2,1} = 1$
$A_{14,15,7,8} = 1$
$A_{14,15,13,12} = 1$
$A_{9,7,2,1} = 1$
$A_{9,7,7,8} = 1$
$A_{9,7,15,16} = 1$

With the help of the above values, the layout obtained is shown in Figure 6.3. From the OFPL, it is clear that the path layout obtained for AGVs to move the material from one manufacturing cell to another manufacturing cells are:

When material moves from Cell 1 to Cell 2, Cell 3 and Cell 4, the paths obtained are $A_{1,10,7,8}$, $A_{1,10,15,16}$ and $A_{1,10,13,12}$ respectively. When material moves from Cell 2 to Cell 1, Cell 3 and Cell 4, the paths obtained are $A_{6,7,2,1}$, $A_{6,7,15,16}$ and $A_{6,7,13,12}$ respectively. When material moves from Cell 3 to Cell 1, Cell 2 and Cell 4, the paths obtained are $A_{14,15,2,1}$, $A_{14,15,7,8}$ and $A_{14,15,13,12}$ respectively. When material moves from Cell 4 to Cell 1, Cell 2 and Cell 3, the paths obtained are $A_{9,7,2,1}$, $A_{9,7,7,8}$ and $A_{9,7,15,16}$ respectively.

The procedure for finding out the optimum flow path layout for AGV discussed above can be easily extended to more typical and more complex layouts.

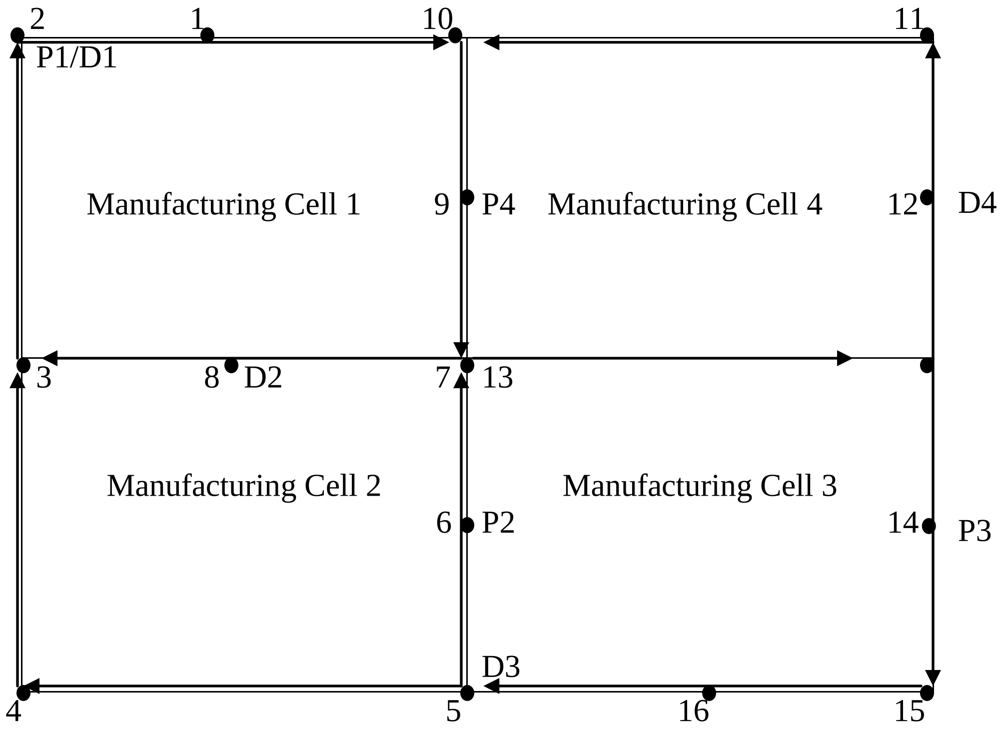


Figure 6.3: Optimal Flow Path Layout of Manufacturing Cells with Directed Arcs

6.7 CONCLUSION

AGVs are widely used as MHS in FMS. In this chapter, various aspects related to AGVs, reviews on AGV path layout problems have been discussed, and the factors affecting the design and development of AGVs are identified. The performance of the overall system is greatly influenced by the guide path layout because it has a direct impact on the travel time, on the installation costs, and efficiency of vehicle dispatching and scheduling, etc.

The objective of this study was to develop an approach to design an optimal flow path for AGVs. The problem was analyzed and developed using 0-1 linear integer programming model to minimize the total distance travelled by individual loaded AGV. To describe the model, a simple example of a manufacturing layout comprises of 4 departments with 16 nodes and 19 arcs is considered and only the movement of loaded vehicles with the unidirectional flow is taken into account. The optimal flow path has been found out with the help of a general linear optimization computer software package, named LINGO 14.

This study has strong implications for researchers as well as manufacturing managers. The researchers may be encouraged to recognize some other issues, which may be important in addressing these factors and this research study can help the management in making decisions and taking actions related to guide path layouts for the improving the efficiency and performance of a manufacturing system. The environments in which the approach is best suited are flexible ones, i.e. more specifically where optimal flow path may change as the material flow intensity in from-to chart changes. Assuming that the departmental layout and other assumptions do not change, constraints of the problem remain the same. All that will change is the coefficients of the objective function.

CHAPTER VII

DESIGN AND DEVELOPMENT OF FLEXIBLE FIXTURE AND PALLET

7.1 INTRODUCTION

Fixtures have been considered as crucial tooling, used to hold the workpiece in its position and orientation based on the design specifications during different operations such as machining, assembly, inspection, etc. (Zhou et al., 2011). In manufacturing, designing of fixtures are one of the significant issues of concern. It is a critical manufacturing activity in the production cycle and has a great effect on product quality, lead time and cost targets (Peshatwar and Raut, 2013). Designing and manufacturing of fixtures is a complicated task as it requires an immense understanding of different areas, such as geometry, tolerances, dimensions, procedures and manufacturing processes (Maniar and Vakharia, 2013). According to Edurne et al. (2014), the design of the fixture should be determined to ensure stability, repeatability, and immobility in the workpiece to be manufactured. An accurate fixture design is critical for quality of a product based on accuracy, and precision of the designed parts (Hashemi, 2014a).

Fixtures are among the most sensitive parts of a transfer system. In manufacturing processes, fixture eliminates frequent checking, positioning, individual marking and non-uniform quality. This increases productivity and reduces operation time (Pachbhai and Raut, 2014). Fixtures should be reusable and changeable to suit the variations of the workpieces, but the custom designed fixtures do not have the flexibility to handle the parts or assemblies of different dimensions and geometry. They are time-consuming and costly to build. This lack of flexibility leads to significant manufacturing costs related with fixturing. Modular fixture elements once disassembled can be re-used for other products to meet workpiece requirements, and they are manufactured with high tolerances (Maniar and Vakharia, 2013). Even though such a modular fixture has been widely applied in industry, it can only fixture a limited number of parts and has to be set up either manually or by robots (Youcef and Buitrago, 1989). So, to reduce manufacturing costs, a flexible fixture (FF) system should be designed to be competent in fixturing as many workpieces as possible.

The development of FF and pallets has been recognized as being of paramount importance in the rapidly evolving field of FMSs. FF are basically a complete system consisting of a number of components assembled so that they can hold and secure the workpiece in its position during different machining operations. In flexible fixturing, a fixture is subjected to the large variety of external forces and torques related to the manufacturing operations in holding the parts of various shapes and sizes (Gandhi and Thompson, 1984; Thompson, 1984; Thompson and Gandhi, 1986). An FMS pallet is usually capable of both serving as a fixture that does not require further positioning when the part is being machined on a machine table and also holding a part while transported between machines (Newman et al., 1991). The increased operating flexibility associated with general purpose pallets may be a key to the efficient scheduling of an FMS. FFs have been suggested as an obvious solution to alleviate and overcome the problem of redesigning because they are adaptable to accommodate a variety of parts and assemblies of different shapes and sizes (Du and Lin, 1998). Approximately 40% of rejected parts are due to dimensioning errors that are attributed to poor fixture design and inaccurate operation of fixtures. Therefore, CAFD has become a research focus in implementing FMS and CIMS.

When human experience in fixture design is utilized, the designing and manufacturing of a fixture can take several days or even longer to complete, and a good fixture design is often based on the designers' experience, his understanding of the products and a try-and-error process (Wang et al., 2010). In order to reduce the design costs and cycle time, the designer needs to be very experienced (Hashemi et al., 2014a). Some factors which should be kept in mind, during designing a fixture includes level of WIP allowed, flexibility of fixtures required, clamping forces required in the fixture, cost effectiveness of a fixture, fixture setup time, capacity of pallets, differences in the part style and size, ease with which parts can be loaded or unloaded from fixture and safety. In this chapter, a case study has been discussed, and designing of a pneumatically control flexible fixture and pallet has been proposed which can handle a variety of parts with different shape and sizes with minor changes in it for performing different operations on drilling heads.

7.2 REVIEWS ON FIXTURE DESIGN AND AUTOMATION

A number of research papers have been published in relevant journals and conferences related to fixture design and automation to achieve cost reduction by means of automation and flexibilization of the production. Farhan and Tolouei (2011) has proposed that computer aided design (CAD) software has been considered as a vital design tool and utilized by numerous researchers, due to the need of more automated modular fixture design methods. With the help of softwares like ICAD and UG-2 modeling interfacing, CAD-based modular fixture designs were developed (Dai et al., 1997). This was followed by using 2D AutoCAD drawings (Surendra et al., 2005) and then it was continued by using AutoCAD with 3D modeling (Xiaoling et al., 2009). An overview of the methodologies of flexible fixturing has been presented by Hashemi et al., 2014a; Hashemi et al., 2014b; Maniar and Vakharia, 2013; Bakker et al., 2012; Boyle et al., 2011; Wang et al., 2010; Kang and Peng, 2009; Boyle et al., 2006; Nee et al., 1995; 2004; Bi and Zang, 2001; Thompson and Gandhi, 1986; Shirinzadeh et al., 1995; Lin and Du, 1996; Shirinzadeh, 1995; Hargrove and Kusiak, 1994; Chang, 1992.

Hashemi et al. (2014a) discussed the developments on CAFD and the case-based reasoning (CBR) approach in their research work. Hashemi et al. (2014b) discussed the concept of fixture design and review of CAFD approaches. Maniar and Vakharia (2013) discussed the concept of fixture design for CNC. Bakker et al. (2012) discussed the concept of active fixturing in their research work. Boyle et al. (2011) and Wang et al. (2010) discussed CAFD in their research work including automatic design and fixture layout optimization. Nee et al. (1995, 2004) also discussed CAD and fixture design verification. Boyle et al. (2006) developed a methodology to classify fixture design information into two libraries: conceptual design information and fixture unit information. Bi and Zang (2001) discussed FF design and automation, reconfigurable fixture components. Shirinzadeh (1995) discussed the classification of FF system from the viewpoint of flexible strategies. Chang (1992) discussed issues of fixture planning for machining processes.

7.2.1 Classification of Fixtures

Numerous authors have classified fixtures in different ways in their research work as mentioned below:

- The most prominent fixturing strategies are generally categorized as: dedicated fixtures, modular fixtures, flexible pallet systems, sensor-based fixture design, phase-change base concepts, base plate concepts, pin-type array fixtures and automatically reconfigurable fixture (Bakker et al., 2012; Kleinwinkel et al., 2006; Nee et al., 1995; Shirinzadeh, 1995).
- Depending on the flexibility of fixtures, they are classified as modular fixtures, dedicated fixtures and general-purpose fixtures, such as conformable and reconfigurable fixtures

(Hashemi et al., 2014b; Wang et al., 2010; Nnaji et al., 1988). Reconfigurable and conformable fixtures can be designed to accept parts of varying shapes and sizes (Wang et al., 2010). Modular fixtures are the most widely used type of reconfigurable fixtures. For job and batch production, modular fixtures are widely used in industry. Due to the capability of modular fixtures to handle inconsistency and standard set of parts, they have been considered as a possible solution for FMS (Price, 2009). The applications of modular fixtures result in reduced lead time and cost of small-volume production with versatile products.

- According to Thompson and Gandhi (1986), Shirinzadeh et al. (1995) and Lin and Du (1996), main approaches for flexible fixturing include: (1) sensory-based fixturing techniques, (2) modular and reconfigurable fixtures, (3) programmable conformable clamps, (4) phase change fixtures and (5) adaptable fixtures.

7.3 DIFFERENT ASPECTS IN FLEXIBLE FIXTURE

Different aspects related to the flexible fixture are discussed below:

7.3.1 Fixture Elements

In general, a fixture consists of three elements (Bakker et al., 2012):

- Locators: It is a rigid element of a fixture with no actuation ability. It is used to locate the workpiece in a desired position and orientation. A typical fixture has at least six locators.
- Clamps: It is a statically positioned, force actuating mechanism of a fixture. It is used to exert a force that securely holds the workpiece in its position against all the forces acting on the workpiece. A typical fixture has at least two clamps.
- Supports: It can be a fixed or adjustable element of a fixture. Due to clamping and machining forces, the problem of part-displacement/deflection may occur. So, in order to prevent the deformation of the part, support are provided and located below the workpiece. They can also improve the stability of the fixture-workpiece system. There is no limitation to the number of supporting elements used in the fixture. A fixture with its elements is shown in Figure 7.1.

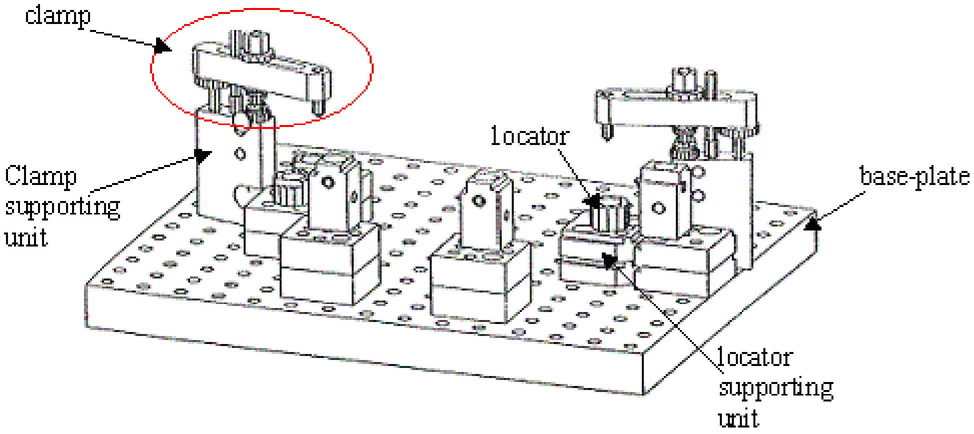


Figure 7.1: A typical fixture (Rong et al., 2004)

Since the workpiece is subjected to the external cutting forces and torque, the three above fixture elements must make sure that the workpiece is positively located, is rigid and assures repeatability. Repeatability refers to the workpiece, and subsequent workpieces can be located by the fixture in precisely the same place (Maniar and Vakharia, 2013).

7.3.2 Fixture System Requirements

Fixtures must satisfy two features, which seem to be opposite:

- To minimize the displacements of the workpiece during the machining process.
- To avoid excessive tensions and strains on the clamped workpiece.

A fixture should locate the workpiece repeatedly and accurately in a position and orientation relative to the reference frame of a machine tool or measurement machine (Bakker et al., 2012). The requirements for designing traditional fixtures also apply to the design of an FF system (Gandhi and Thompson, 2008). These include positive location, rigidity, repeatability, minimum distortion of workpieces, tolerance to small variations in workpiece geometry and reliability as discussed below:

- Positive Location: A fixture must hold the workpiece precisely in space to prevent each of the spatial movements, i.e., linear movement in either direction along X, Y and Z axes and rotational movement in either direction about each axis.
- Repeatability: Identical workpieces should be located by the fixture in precisely the same place on repeated loading and unloading cycles.

- Rigidity: The fixture must ideally hold the workpiece rigidly fixed against all external force fields.
- Interference: The fixture elements must ensure that the part is accessible to the cutting tool and in addition, must provide ease of loading and unloading.
- Positioning Fundamentals (3-2-1 principle): In order to meet the positive location criterion, the fixture must position the workpiece in each of three planes.

7.3.3 Locating Principle (3-2-1 Principle)

According to Black and Kohser (2008), locating is considered as a critical factor to hold and orientate the workpiece in its position during the different machining processes thoroughly. Hashemi (2014b) also stated that to locate and clamp the workpieces and to support the machining operations, the fixtures are widely used as a work-holding device. To restrict the degrees of freedom (DOF) of the workpiece, locators are used, and these locators should be capable enough to keep the workpiece in place against all the cutting forces during machining operations (Krsulja et al., 2009). DOF are shown in Figure 7.2.

The 3-2-1 principle is the most widely used method for locating. In order to meet the positive location criterion, the fixture must position the workpiece in each of three planes. This positive location criterion involves support at three points in the first plane which is followed by assigning a second plane which is perpendicular to the first. This is done by orienting the part in the second plane against any two points. A third plane perpendicular to each of the other two is then defined by designating one point in it. If a part is in contact with three points in the first plane, two points in the second plane, and a single point in the third plane (the three-two-one rule) as shown in Figure 7.3-7.5, then the positive location for that part is assured. In order to ensure maximum stability, the support points in each plane are selected to be as far as possible. In addition, it may be necessary to provide redundant supports in order to satisfy additional constraints imposed on vibration levels and deflections (Gandhi and Thompson, 2008).

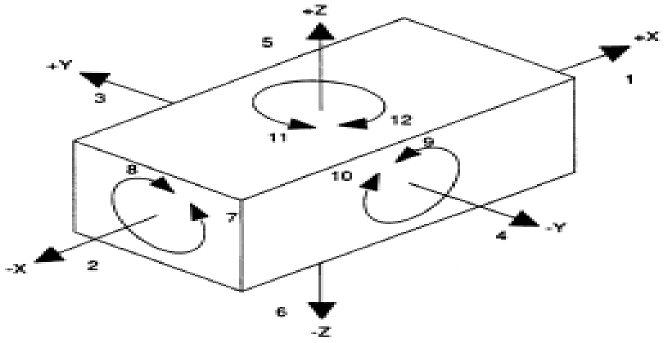


Figure 7.2: Degrees of freedom (DOF) (Carrlane catalogue, n.d.)

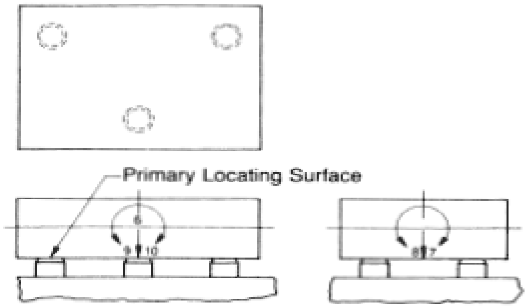


Figure 7.3: Three supports on the primary locating surface restrict five degrees of freedom (Carrlane catalogue, n.d.)

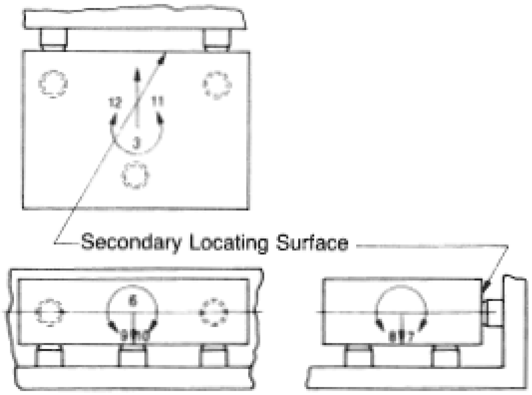


Figure 7.4: Adding two locators on a side restricts eight degrees of freedom (Carrlane catalogue, n.d.)

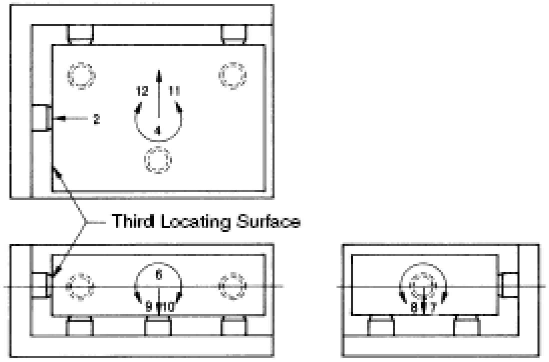


Figure 7.5: Adding a final locator to another side restricts nine degrees of freedom, completing the 3-2-1 location (Carrlane catalogue, n.d.)

7.4 FIXTURE DESIGN PROCESS

Design and fabrication of fixture form a significant portion of the needed investment and total process planning time for the manufacturing system. Therefore, improvements in flexible fixturing technologies could have vital economical impacts on the manufacturing cost (Kamarthi et al., 2009). Furthermore, the requirements for flexibility, turn-over times, product quality, material price, the number of products and so on determine the financial investment that a manufacturer makes in FF systems (Bakker et al., 2013).

Fixture design is a complex procedure which requires a designer with extensive knowledge and experience (Sanchez et al., 2009). The fixture design process is based on heuristic knowledge of tool designers, i.e., it is a highly subjective process (Hargrove and Kusiak, 1994). Moreover, for each step of fixture design, many design requirements should be considered at the same time. Fixture design includes the recognition of clamps, locators and support points and the selection of the corresponding fixture elements for their respective functions. Four main stages of a fixture design process are: setup planning (D1), fixture planning (D2), fixture unit/configuration design (D3) and fixture design verification (D4) (Wang et al., 2010; Boyle, 2006; Rong et al., 2005; Kang et al., 2003a, 2003b, 2003c; Nee et al., 1995). The basic steps of fixture design are discussed below in detail and shown in Figure 7.6.

7.4.1 Setup Planning (D1)

This step involves the determination of a number of tasks for each setup and the total number of setups needed to carry out all the manufacturing operations. In setup planning, the considerations

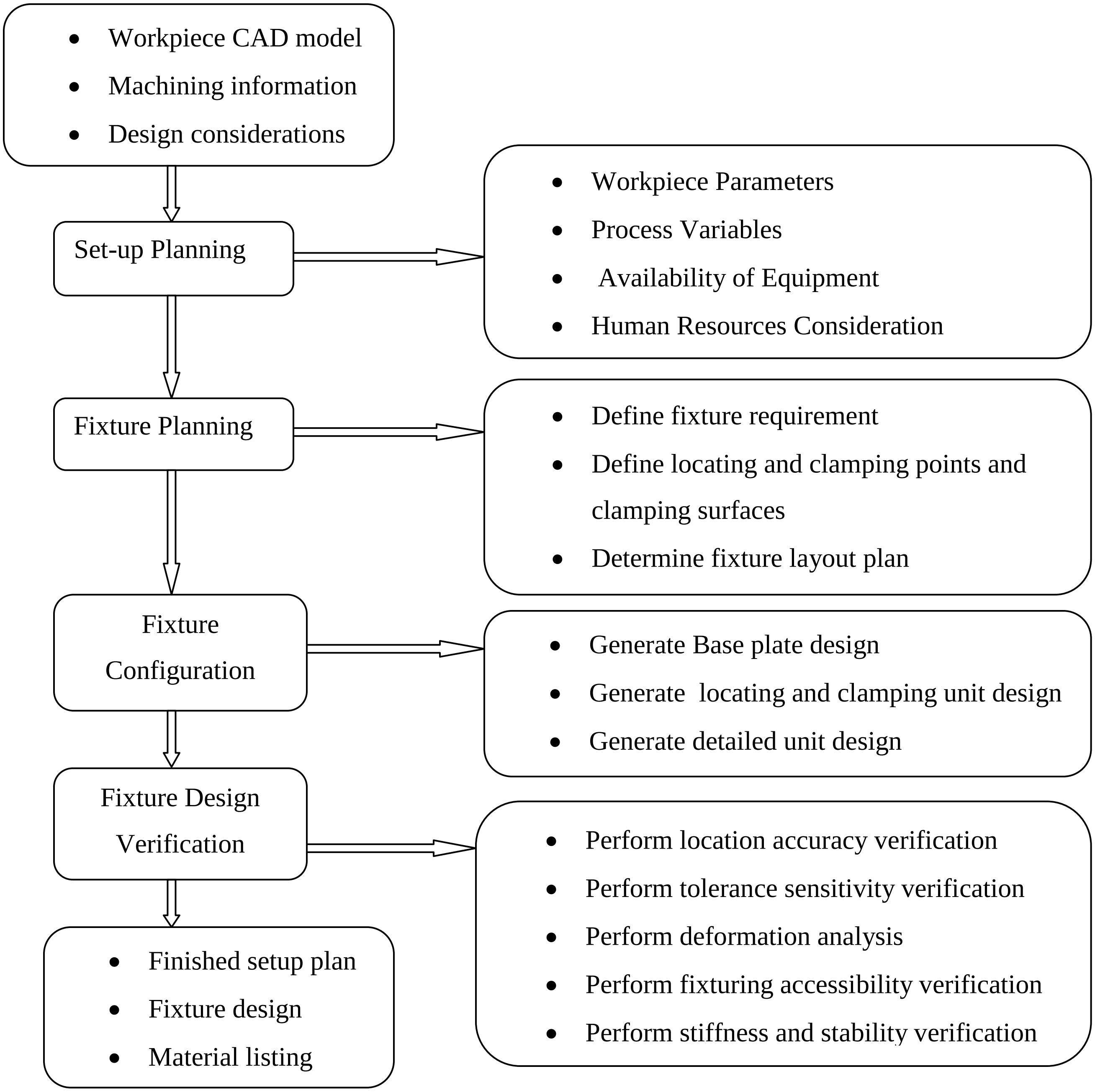


Figure 7.6: Basic steps of fixture design

that need to be addressed are workpiece parameters, process variables, availability of equipment and human resources. Final design of fixture is significantly influenced by the workpiece parameters, so they have been considered as the most important factors. Generally, the considerations that must be incorporated in workpiece parameters are: the size and shape of the workpart, the properties of the part material, the accuracy required, the locating and clamping surfaces and the size of the run. Process variables take account of the type and number of processes that should be carried out to manufacture the part, sequence of processes, inspection requirements and time boundations. Typically, the considerations included in equipment criteria are: the type and number of machines available, availability of cutting tools, availability of inspection equipment and facilities**.** Human resources include the availability of the end user or operator of the equipment.

7.4.2 Fixture Planning (D2)

In the case of fixture planning, depending on the design of parts and process requirements, the locating and clamping of the workparts are determined. Proper clamp in a fixture directly influences the accuracy and quality of the work done and production cycle time (Pachbhai and Raut, 2014). A lot of experience is required in case of fixture planning because of the output of this step, automatically configured the fixture layout to hold the part firmly (Nelaturi et al., 2014). A number of points that must be considered during this step are: the type and number of fixtures required, the orientation of fixture corresponding to the orientation of the joining or machining operations, which fixtures have to handle, the surfaces upon which the locators and clamps must act, as well as the actual positions of the locating and clamping points on the workpiece (Maniar and Vakharia, 2013). The position and number of locating points must be such that the workpiece is adequately constrained during the manufacturing process.

7.4.3 Fixture Configuration Design (D3)

The layout of a set of locators and clamps on a workpiece surface is determined in the case of fixture configuration stage such that the workpiece is completely restrained (Maniar and Vakharia, 2013). To fulfill the conditions for stable workholding, contact(s) between part and locators is required at all times, and the clamping force must be large enough to maintain force closure under any external loading of bounded magnitude (Bakker et al., 2013). A detailed analysis is examined to locate and position the workpiece, during the design phase. Generate the bottom/side locating components/units, top/side clamping units and mount fixture components/units onto the table. Fixture configuration designs determine a concrete fixture configuration, including flexible variables or assemblies based on the characteristics of a particular workpiece in the families. Fixture assembly can be done manually or in an automated system. Many researchers analyzed fixture assembly using robots (Chan et al., 1990). Shirinzadeh (1994) discussed a prototype system for FFs in robotic assembly using a CAD package that is capable of setting up a number of fixture modules and automatically changing and adjusting the assembly robot without human intervention. The art of fixturing is acquired through trial and observation, and these are the skills and knowledge that the fixture designer develops over a period of time.

7.4.4 Fixture Design Verification (D4)

According to Hashemi et al. (2014a), after designing the fixture, it is verified to analyze the capability of the geometric constraints, tolerance achieved, deformation and fixture-workpiece system stability. At this stage, fixture performance is analyzed (Nee et al., 1995; Rong et al., 2005; Leopold and Hong, 2009). The fixture is set up on the machine, and several parts are run. The verification of the fixture design is an important step in the design cycle (Nee et al., 1995 and Rong et al., 2005). According to Shirinzadeh and Tie (1995), it must detect any obtrusion that may arise during the fixture manufacturing. Verification is also required in the use of a fixture system to justify whether the system in good condition. Fixture design verification usually consists of a tolerance sensitivity, accessibility, stiffness, stability, and deformation analysis (Bakker et al., 2012; Bi and Zhang, 2001).

7.5 COMPUTER AIDED FIXTURE DESIGN (CAFD)

In CAFD, computers are used to assist the process of fixture designing (Price, 2009). CAFD have grown tremendously since the 1980s and to enhance the process of fixture designs a lot of work has been done (Peng et al., 2011). Although modular fixtures are widely used in organizations as FFs, they are restricted in large-batch and mass productions where dedicated fixtures are used. The customized fixtures can be quickly designed and manufactured by utilizing CAFD with 3-D lithographic and/or CNC machining techniques (Wu et al., 1997). The time taken in the designing process has been reduced by computers to a great extent because designers can identify potential problems and undertake different ideas without physically creating the fixture (Hashemi et al., 2014a). Price (2009) stated that time and costs could be kept low with CAFD by avoiding mistakes and keeping a designer from missing steps. In order to keep the number of errors minimum in the finished product, they are made according to really tight tolerances (Hou and Trappey, 2001).

Over the past decade, much focus has been put on intelligent methods for CAFD to seek a technical breakthrough in embedding more design knowledge into semiautomatic or automatic

CAFD systems as shown in Table 7.1, where D1, D2, D3 and D4 are four main stages of a fixture design process as discussed above. According to Hashemi et al. (2014a), efforts made by the researchers over the past few decades in the area of fixture design have resulted in a wide range of CAFD applications using various intelligent methods such as expert systems, CBR and genetic algorithm (GA). Boyle et al. (2011) studied the most recent works published about CAFD. They state that the CAFD is segmented in nature and greater focus is needed on supporting detailed fixture design. They developed a CBR fixture design method. According to Wang and Rong (2008), numerous techniques have been used in the fixture designing such as CBR, GA, rule-based reasoning (RBR), geometric analysis, etc.

CBR is an artificial intelligence technique in which the problems are solved using past experiences (Kolodner, 1993). CBR allows a user to learn from previous mistakes by keeping them stored and easily available. It utilizes knowledge and experience to overcome new challenges. Furthermore, a lot of good design cases and abundance of technical knowledge are available readily in manufacturing companies which can be utilized as knowledge and experience in using the CBR-based systems for fixture design. This is why CBR is one of the most effective techniques in this sector (Hashemi et al., 2014a). According to Aamodt and Plazas (1994), four main modules in CBR are: retrieve, reuse, revise and retain.

RBR is an experts’ system approach that uses induction rules to make a decision if a new problem should be further analyzed or not (Peng et al., 2011). Nnaji and Alladin (1990) and Kumar et al. (1992) used RBR technique. In their research, they carried a limited assessment of the likely displacement at each locating point caused by the machining forces and implemented an easy justification module that utilized heuristic rules to make a decision if a dedicated or modular fixture design should be produced. Nnaji and Alladin (1990) utilized RBR technique for fixturing on a CAD system by means of a FF, based on the information of the geometry of the workpiece, machines, and machining processes. Nee and Kumar (1991) also elaborated an automated rule-based fixture design.

Typically, a geometry-based system is designed where the dimensions of the individual element are generated in association with the primary dimension of that element through parametric dimension links. This is augmented with a relation knowledge base of how various elements are configured to create one unit (An et al., 1999). According to Bi and Zhang (2001), a geometry-oriented approach is a widely used technique in which most of the information needed can be retrieved from CAD systems. Wu et al. (1998) stated that the geometric approaches have been utilized to identify the significant dimensions of a fixture unit.

In some fields of fixture design, to generate an optimal fixture configuration layout, GA is utilized. The layouts help to determine the optimal positions at the contact point between fixture and workpiece. GA is an evolutionary algorithm, which is often used to solve optimization problems (Hashemi et al., 2014a). According to Kumar and Melkote (2000), in fixture layout optimization, GA is typically used to find out the optimal clamping condition for an elastic workpiece. In order to minimize the deformation in the workpiece due to the clamping and machining forces, they utilized GA to create the new contact point sets till an optimum condition is obtained. Wu and Chan (1996) ignored elastic deformation of the workpiece due to clamping and machining forces and optimized the fixture layout model using GA. In Table 7.2, the important intelligent methodologies in CAFD with their procedures, applications, and references are considered.

Table 7.1: CAFD Literature (Wang et al., 2010)

Author	**Method**	**Level of detail**				**Application**
		D1	D2	D3	D4	
Aoyama et al. (2006)	GA	✓	✓			
Boyle et al. (2011)	CBR	✓	✓	✓		
Choubey et al. (2005)	GA	✓	✓		✓	Machining fixtures
Chen et al. (2002)	CBR	✓				
Fan and Kumar (2005)	CBR	✓	✓			
Kaya (2006)	GA	✓	✓		✓	Machining fixtures
Kumar et al. (2000, 2002)	GA	✓	✓	✓	✓	Machining fixtures
Li et al. (2001a, 2001b)	GA	✓	✓		✓	Sheet metal assembly with laser welding
Subramaniam et al. (2001)	GA	✓	✓			

Author	Method	Level of detail				Application
		D1	D2	D3	D4	
Subramaniam et al. (1999)	GA	✓	✓			
Wang et al. (2010)	CBR	✓	✓	✓		Modular fixtures for welding

Table 7.2: Intelligent methodologies in CAFD with their applications

Methodologies	Procedure	Application	Mostly integrated with	References
CBR	Design based on basic heuristic rules	Modular fixture, fixture planning, unit design and fixture design verification	RBR	Kolodner (1993); Aamodt and Plaza's (1994); Sun and Chen (1995); Boyle et al. (2011); Wang and Rong (2008); Hashemi et al. (2014a)
GA	Optimization process by generating possible solutions	Optimal fixture layout configuration, conceptual design of fixture, fixture planning, and fixture design verification	Finite element method (FEM)	Wu and Chan (1996); Kumar et al. (1999); Kumar and Melkote (2000); Bi and Zhang (2001); Wang and Rong (2008); Hashemi et al. (2014a); Hashemi et al. (2014b)

Methodologies	Procedure	Application	Mostly integrated with	References
Geometric approaches	Pre-existing mathematical relationships based on parametric dimension relationships	Workholding verification, selection of fixture point, frictionless assemblies, polygonal parts, modular fixture, fixture design verification, fixture planning and fixture unit design	RBR	Markenscoff et al. (1990); Wolter and Trinkle (1994); Brost and Goldberg (1994); Willy et al. (1995); Wu et al. (1998); Bi and Zhang (2001); Wang and Rong (2008); Hashemi et al. (2014a); Hashemi et al. (2014b)
RBR	Design based on basic heuristic rules	Face milling planar part, flexible fixtures, modular fixture, setup planning, fixture planning, unit design and fixture design verification	CBR	Nnaji and Alladin (1990); Kumar et al. (1992); Bi and Zhang (2001); Wang and Rong (2008); Peng et al. (2011); Hashemi et al. (2014a); Hashemi et al. (2014b)

7.6 PNEUMATIC POWER FIXTURES

Different actuator solutions have been addressed in the literature, in search for the best solution to meet the fixture requirements of each application in terms of: stiffness of the solution, the geometrical field of application (large or small part fixture), the accuracy of the positioning and cost (Edurne et al., 2014). The most commonly employed are: electro mechanic actuators, hydraulic or pneumatic actuators, and piezoelectric actuators. Concerning pneumatic actuators, make the actuator function via compressible gas energy. Pneumatic systems are widely used in the industrial sectors for the driving of automatic machines. One of the most innovative solutions on fixturing large and difficult-to-handle parts using pneumatic solutions are the pin array type flexible machining fixtures (Hurtado and Melkote, 2002). These fixtures feature an array of pins that hold parts by conforming to their shape. Pneumatic actuators have many distinct characteristics of energy-saving, cleanliness, high efficiency, simplicity of design and control, reliability, consistency and repeatability of operations, controlled clamping forces, economical, automatic sequencing, high adaptability to the harsh environment, safety, etc. Therefore, use of pneumatic actuators result in increased production speed and productivity.

7.7 A CASE STUDY

For designing a pneumatically controlled FF of a particular type, a case study was carried out in XYZ manufacturing industry. This industry deals in manufacturing of pneumatically controlled drilling and milling machines, manufacturing of twist drills, multi-tooth cutters, broaching tools and some other type of tools. A particular case was studied in which customers needed a drilling machine with multi-spindle drilling attachment along with twist drills and a flexible fixture which can handle workparts of different shapes and sizes. The customer also demanded the flexibility to drill on the component surface at different angles in a single setting. Within the scope of present research, designing of a pneumatically operated flexible fixture with pallet which can handle a variety of parts with different shape and sizes with minor changes in it for performing different operations on drilling heads has been discussed here, as per requirement of the customer for the current component as shown in Figure 7.7.

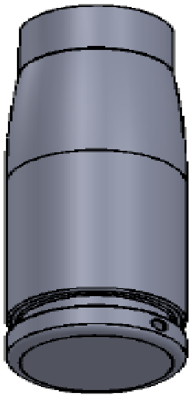


Figure 7.7 Component for drilling operation

7.7.1 Drilling Head

On conventional drilling machine, only one operation can be performed at a time, but conventional drilling machine with multi-spindle drilling head attachment can be utilized to carry out three operations at a time, also different operations like drilling, reaming, countersinking or spot facing simultaneously. The customer demands the product of right quality in the right quantity at the right cost and at the right time. One way to attain this is by using multi-spindle drilling head (Shingavi et al., 2015). These machines are easy to operate, user-friendly and advanced technology machines.

To boost the production of machine tools, multi-spindle drilling heads are widely utilized in manufacturing industries. The multi-spindle drilling head attachments are easy to mount on the drilling machine, wherein the MT-2 taper arbor directly fits into the drilling machine sleeve, if necessary a support sleeve can be attached to the top casing plate for extra stability. In these attachments, three spindles are driven simultaneously which carry three drill chucks. The drill chucks can accept twist drills, reamers, countersink drills or spot facing cutters to carry out the required desired operation (Shingavi et al., 2015). As per the requirement of different operations, the center distance between the spindles can be modified in any position. These drill spindles are attached to the main spindle by universal joints in order to modify the center distance between them, (Udgave and Khot, 2011). A multi-spindle drilling attachment with two spindles driven by a single power head is shown in Figure 7.8 for better understanding.

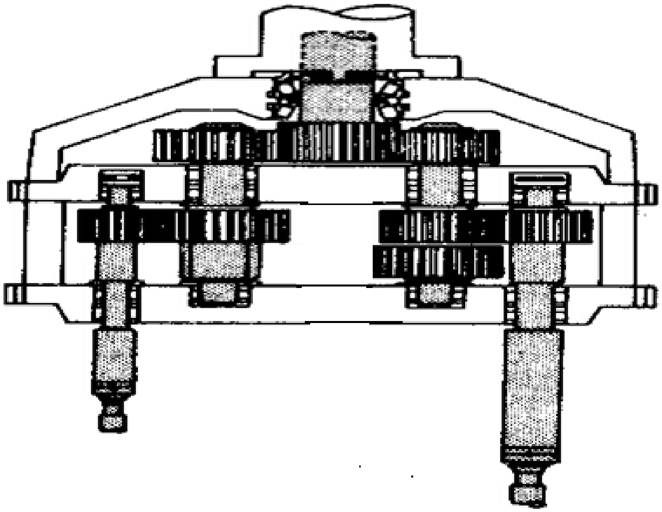


Figure 7.8: Multi-spindle drilling head with two spindles (Udgave and Khot, 2011)

7.8 DESIGNING OF FLEXIBLE FIXTURE

Generally, a FF consists of a number of fixture components which are assembled in a proper sequence. A CAD-based 3D-modeling has been used to find out the types of fixture components and their assembly sequence because with the help of 2D drawings and physical models, fixture elements and assembly sequences can be determined but these are not competent methods in the world of advanced manufacturing technologies. Farhan and Tolouei (2011) stated that by defining the relationships between fixture elements and workpieces in the CAD-based 3D-modelling system, designers could find out the proper FF designs. In designing of flexible fixture systems, the following parameters should be considered:

- Designing environment.
- Geometry and shape of workpiece.
- Machining operations.

In the case of modeling environment, 3D-SolidWork has been utilized as the suitable CAD software to carry out the FF designing. The geometry and shape of workpiece is a crucial parameter in determining the suitable FF system and locating and clamping procedures. In designing of FF, the points that should be considered are quantity of workpieces to be machined, type of operations to be performed, locating method, clamping mechanism and so on. SolidWork software provides an excellent 3D platform to model FF components and to determine assembly sequences. This is accomplished by applying mating relationships after considering workpiece setup and fixture elements to achieve the optimum FF assembly design as shown in Figure 7.9.

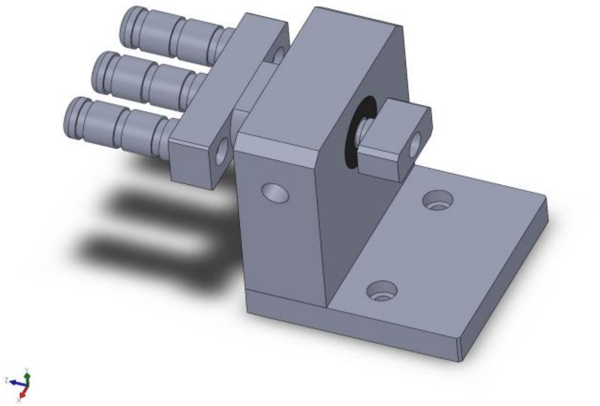


Figure 7.9: Assembled fixture design

The fixture shown here consists of the pallet, fixture base, mandrel base, and mandrels. These mandrels are used to hold the workpieces for the machining operation. The material used for fixture and mandrel is EN-31, and nitriding has been done on the surfaces. As per the requirement of the customer, the shape of the mandrel and/or the mandrel base can be changed for machining a variety of workpieces with different shapes and sizes. A number of fixtures can be attached to the base plate with a gap according to the requirement of a particular machine to perform the operation. On the base plate, semi-rotary drives/cylinders can also be attached.

The semi-rotary drive is shown in Figure 7.10. In these drives, a rotary vane is used to transmit the force to the drive shaft. The swivel angle can be adjusted to 0°-184°. Stop blocks absorb the forces which may occur during operation and for this purpose the adjustable stop system is separated from the rotary vane. The flexible plastic plates are used to cushion the forces at the end positions. The cushioning angle on each side is approx. 1.6° maximum at 8 bar. If after the swivel process, the kinetic energy is converted by cushioning, the drive shaft swivels back by a corresponding angle. More flexibility can be added with the use of semi-rotary drives because, the swivel angle can be adjusted to any angle between 0° -184°. For example, if the angle is set at 90°, then machining or drilling can be done in one setting on two surfaces perpendicular to each other. Photo sensors can also be used just before the drilling heads to sense the presence of a workpiece. If the workpiece is not available in the fixture, in that case, the machine will not work. For automatic unloading, pneumatic grippers and cylinders can be used.

Figure 7.10: Semi-rotary drives

7.9 CONCLUSION

Basic steps of fixture design process, significant researchers and requirements of fixtures over time, 3-2-1 locating principle and fixture elements have been discussed in this chapter. Significant and relevant researches in the area of CAFD using some intelligent techniques that have been commonly utilized in automation have been examined. A case study and designing of a pneumatically operated FF with pallet has been discussed which can handle a variety of parts with different shape and sizes with minor changes in it for performing different operations on drilling heads. The proposed design of pneumatically operated FF can be used in any manufacturing industries which are dealing in drilling operations. A CAD-based 3D-modelling has been used to find out the types of fixture elements and the assembly sequence. The proposed fixture will fulfill the customer production target and enhance efficiency. Drilling heads discussed here are considered as electro-pneumatically controlled. From this study, management can obtain better guidelines and strategies which will be helpful in taking various decisions relating to designing and manufacturing of fixtures to improve the performance of the system.

CHAPTER VIII

A COMPARATIVE STUDY OF MCDM APPROACHES FOR PRIORITIZING THE MANUFACTURING SYSTEMS

8.1 INTRODUCTION

In the current scenario, due to the high expectations and rapidly changing demands of the customers', it has become quite difficult to survive for most of the manufacturing industries in developing countries. Gunasekaran et al. (2008) proposed that in order to deal with the market unsteadiness, industries now focus upon to speed quality and flexibility rather than cost. They have realized that it is the time to upgrade their manufacturing systems. To cope up with such an environment, it is the time to transit from traditional manufacturing system to AMS like CNC, FMS, HFMS and CIM systems. To meet the challenges forced by international rivalry, rapidly changing demands of customers and rapid delivery to market, the organizations are attracted to the implementation of these advanced manufacturing systems (Nagar and Raj, 2012).

Kumar et al. (2006) stated that industries adopt FMS to meet the growing demands of customized production. According to Kumar and Sridharan (2007), an FMS is a growing technology appropriate for mid-volume and mid-variety production. FMS is equipped with several computer-controlled machine tools interconnected by automated MHSs to offer high productivity and flexibility (Singholi et al., 2012). Companies adopting flexible manufacturing technology rather than conventional manufacturing technology can react more quickly to market changes.

Indian organizations are utilizing traditional manufacturing systems for quite a long period of time. They are using CNC machines to increase the production and to enhance the products quality. Although CNC machines are built with several features and used in Indian industries, most of them do not have the advanced features and facilities required in FMC and FMS applications (Rao and Deshmukh, 1994). Lack of enthusiasm has been noticed among the industries to implement the advanced stage of manufacturing, i.e., FMS or CIM (Raj et al., 2006). According to Nagar and Raj (2012), reasons for such reluctance have been the high cost of these AMSs, non-availability of reliable vendors, the abundant availability of human labour in a country like India and many others. The design of an FMS requires high investment, and the decisions at this stage have to be made very carefully to ensure that the highly automated manufacturing system will successfully satisfy the demands of an ever-changing market (Park, 2005).

Developments in CAD applications and CAM based systems introduced the concept of CIMS which is collectively named as AMT (Nagalingam and Lin, 2008). The CIMS is a highly automated production facility and consists of the integrated functional units along with latest technologies. It provides flexibility as well as data driven computer integration for a manufacturing organization, in which the manufacturing technology utilized is intelligent enough to process the activities with less human intervention (Kumar et al., 2005). However, human resources are required to operate, manage, maintain and service the system. The MHS plays a crucial role in FMSs. This is the MHS which requires the main attention of researchers, and it is the focal point through which the idea of HFMS is originated (Nagar and Raj, 2012).

HFMS means the involvement of human element in FMS. The main idea behind HFMS is to replace complex automated material handling components with human element in developing countries like India where labour is very cheap and easily available and adopting the other components such CNC machines, flexible special purpose machines (SPMs), co-ordinate measuring machines (CMMs), CAD, computer aided manufacturing (CAM) and machine vision systems in the similar way as they are used in an FMS (Nagar and Raj, 2012).

Raj et al. (2007b) have also proposed the use of human labour in place of automated material handling devices. Maffei and Meredith (1994) discussed the importance of human element in the successful implementation of flexible manufacturing technology. Mason and Baines (2005) have also analyzed the importance of human element in the design using simulation technique. They have analyzed the performance of the workers in the manufacturing system, design, and simulation. More skilled and versatile workers mean more flexibility of FMS.

There are various measures which affect these manufacturing systems. Therefore, it is essential to analyze these measures. The four measures used for the analysis are flexibility, MHS, performance, and fixture and pallets. AGV is considered in this study with respect to MHS. In this chapter, ANP and AHP approaches have been utilized to rank or prioritize the alternatives by analyzing the weights of measures and their sub-measures.

The main research objectives of this chapter are:

- To identify the measures and sub-measures which are associated with the manufacturing systems
- To evaluate and rank/ prioritize the alternatives using ANP and AHP

8.2 IDENTIFICATION OF MEASURES AND SUB-MEASURES

Through the literature review, questionnaire survey and interactions with practicing managers and academicians most significant measures and sub-measures which could affect the overall efficiency of a manufacturing system have been identified. The main objective of the questionnaire was to rank the different factors as per the experts' opinion. In total, 4 measures and 20 sub-measures are identified as shown in Table 8.1.

Table 8.1: Measures and sub-measures with their references

Factors	**References/Sources**
Flexibility	
Setup or changeover time	De Groote (1988); Groover (2003)
Type of operations to be done on machine	Groover (2003)
Skills and versatility of workers in the system	Piore and Sabel (1984); Groover (2003)
Type of machines	Groover (2003)
Variety of parts/products	Bayazit (2005); Groover (2003); Raj et al. (2012); Sujono and Lashkari (2007)
Performance	
Processing time	Mosconi and Mcnair (1987); Johnson (1988)
Multi-functional team	Maffei and Meredith (1994); Rao and Deshmukh (1994); Nagar and Raj (2012)
Number of parts produced	Bayazit (2005)

Factors	References/Sources
Performance	
Lead time	Groover (2001); Zhang et al. (2002); Jain and Raj (2016)
Motivational Schemes	Grover et al. (2004); Theodorou and Florou (2008)
Material Handling System	
Traffic management technique	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Groover (2008); Zeng et al. (1991); Ho (2000); Malmborg 1992;
Positioning of idle vehicles	Raj et al. (2007a); Vis (2006); Mahadevan and Narendran (1990); Malmborg (1990);
Battery management	Raj et al. (2007a); Vis (2006); Shankar and Vrat (1999); Le-Anh and De-Koster (2004);
Capacity of buffer for the vehicle	Sharma (2012); Raj et al. (2007a); Vis (2006); Mantel and Landeweerd (1995);
Failure management	Raj et al. (2007a); Vis (2006); Le-Anh and De-Koster (2004);
Fixture and pallets	
Flexibility of fixtures	Jain and Raj (2015)
Fixture setup time	Bi and Zhang (2001)
Capacity of pallet	Expert opinion
Ease with which parts can be loaded or unloaded from the fixture	Bi and Zhang (2001)
Clamping force required in the fixture	Bi and Zhang (2001)

8.3 METHODOLOGIES

Various MCDM methods have been used in the literature by numerous authors such as GTA, AHP, ANP, SAW, WPM, MOORA, compromise ranking method (VIKOR), etc., to help out the decision makers in making good judgments. According to Azadeh et al. (2010), the decision-making technique should be employed according to the input of the critical factors so that the right decision can be made and the maximum efficiency can be achieved. In this chapter, two decision-making approaches which are ANP and AHP are used in order to rank or prioritize the alternatives.

8.3.1 Prioritization of Manufacturing Systems with ANP

Step 1: In this step, the problem is transformed into a hierarchy in order to locate the measures, sub-measures, and alternatives into different levels so that they can be analyzed by the ANP approach. The ANP model is shown in Figure 8.1. The goal of the problem is placed at the top level of the ANP model, and the measures (flexibility, MHS, performance, fixture and pallets) are placed at the second level. The sub-measures are placed in the third level: five sub-measures are considered for each measure. Four alternatives i.e., FMS, HFMS, CIM and CNC system, considered for this research are placed at the last level of the model.

Step 2: Assuming that no dependence among the measures, pairwise comparison of the measures with respect to the goal is done with 1 to 5 scale. The pairwise comparison matrix is shown in Table 8.2. Eigen value and consistency ratio are determined. Generally, a CR of 0.1 or less is considered as acceptable, and it reflects that the judgment made has a good consistency.

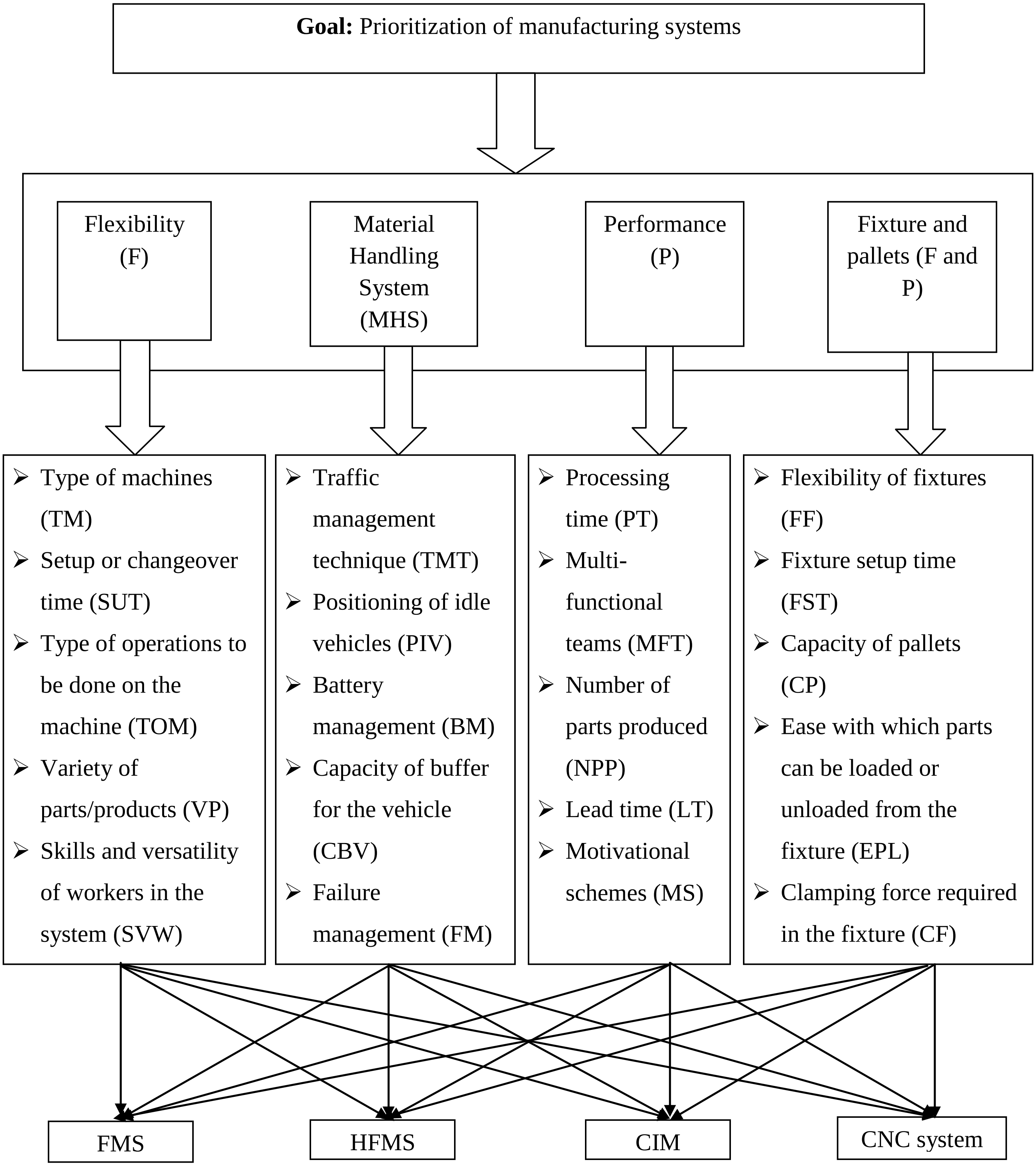


Figure 8.1: The ANP model

Table 8.2: Pairwise comparison of measures (W_1)

Measures	F	MHS	P	F and P		Priority vector
F	1	3	2	2		0.420
MHS	1/3	1	1/2	3		0.190
P	1/2	2	1	2		0.269
F and P	1/2	1/3	1/2	1		0.121

Step 3: For determining the inner dependence among the measures, impact of each factor on every other factor is analyzed with the help of pairwise comparisons. Based on the inner dependencies, pairwise comparison matrices for measures are shown in Tables 8.3-8.6. The priority vectors are shown in the last column of Tables 8.3 to 8.6.

Table 8.3: Inner dependence matrix of flexibility measures

F	MHS	P	F and P			Priority vector
MHS	1	1/3	2			0.249
P	3	1	3			0.594
F and P	1/2	1/3	1			0.157

Table 8.4: Inner dependence matrix of performance measures

P	F	MHS	F and P			Priority vector
F	1	1/2	3			0.320
MHS	2	1	4			0.558
F and P	1/3	1/4	1			0.122

Table 8.5: Inner dependence matrix of MHS measures

MHS	F	P	F and P			Priority vector
F	1	1/2	1/3			0.163
P	2	1	1/2			0.297
F and P	3	2	1			0.540

Table 8.6: Inner dependence matrix of fixture and pallet measures

F and P	F	MHS	P			Priority vector
F	1	3	1/2			0.333
MHS	1/3	1	1/3			0.140
P	2	3	1			0.528

Using the computed relative importance weights, the inner dependence matrix of the measures (W_2) is

$$W_2 = \begin{pmatrix} 1 & 0.16 & 0.32 & 0.33 \\ 0.25 & 1 & 0.56 & 0.14 \\ 0.59 & 0.30 & 1 & 0.53 \\ 0.16 & 0.54 & 0.12 & 1 \end{pmatrix}$$

Step 4: In this step, the interdependent priority (W_{measure}) of the measures is determined as follows: $W_{\text{measure}} = W_2 \times W_1$. Significant differences are observed in the results obtained for the measure priorities (W_1), when the interdependent priorities of the measures and dependencies are ignored.

$$W_{\text{measure}} = W_2 \text{ x } W_1 = \begin{pmatrix} 0.157 \\ 0.272 \\ 0.370 \\ 0.201 \end{pmatrix}$$

$$W_{\text{sub-measure}}(\text{F}) = \begin{pmatrix} 0.130 \\ 0.205 \\ 0.293 \\ 0.223 \\ 0.148 \end{pmatrix} \qquad W_{\text{sub-measure}}(\text{MHS}) = \begin{pmatrix} 0.257 \\ 0.155 \\ 0.304 \\ 0.127 \\ 0.160 \end{pmatrix}$$

$$W_{\text{sub-measure}}(\text{P}) = \begin{pmatrix} 0.198 \\ 0.237 \\ 0.153 \\ 0.230 \\ 0.180 \end{pmatrix} \qquad W_{\text{sub-measure}}(\text{F and P}) = \begin{pmatrix} 0.139 \\ 0.261 \\ 0.205 \\ 0.246 \\ 0.150 \end{pmatrix}$$

Step 6: Now the overall priorities of the sub-measures are computed by multiplying the interdependent priorities of measures as calculated in step 4 with the interdependent local priorities of sub-measures determined in step 5 as shown in Table 8.7. The $W_{\text{sub-measures}}$ (global) vector is obtained by using the overall priority vector values of the sub-measures in the last column of Table 8.7.

Table 8.7: Overall priorities of sub-measures

Measures	Priority vectors	Sub-measures	Priority vectors	Overall priority
F	0.157	TM	0.130	0.020
		SUT	0.205	0.032
		TOM	0.293	0.046
		VP	0.223	0.035
		SVW	0.148	0.023
MHS	0.272	TMT	0.257	0.070
		PIV	0.155	0.042
		BM	0.304	0.083
		CBV	0.127	0.034
		FM	0.160	0.043
P	0.370	PT	0.198	0.073
		MFT	0.237	0.088
		NPP	0.153	0.057
		LT	0.230	0.085
		MS	0.180	0.066
F and P	0.201	FF	0.139	0.028
		FST	0.261	0.052
		CP	0.205	0.041
		EPL	0.246	0.049
		CF	0.150	0.030

Step 7: Here, the importance degrees of the alternative manufacturing systems with respect to each sub-measure are determined. Using experts' opinion, the eigenvectors are computed by analyzing these matrices and the W_4 matrix: importance degrees of alternatives are:

$$W_4 = \begin{pmatrix} .406 & .172 & .408 & .146 & .167 & .318 & .332 & .325 & .314 & .283 & .275 & .146 & .455 & .303 & .187 & .223 & .108 & .269 & .292 & .269 \\ .287 & .084 & .319 & .100 & .106 & .450 & .444 & .427 & .469 & .490 & .463 & .104 & .321 & .460 & .108 & .509 & .187 & .190 & .413 & .420 \\ .218 & .243 & .167 & .246 & .319 & .154 & .152 & .169 & .138 & .152 & .176 & .311 & .131 & .143 & .292 & .175 & .292 & .420 & .187 & .190 \\ .089 & .501 & .106 & .507 & .408 & .077 & .072 & .079 & .080 & .076 & .085 & .439 & .093 & .094 & .413 & .094 & .413 & .121 & .108 & .121 \end{pmatrix}$$

$$W_{\text{sub-measures}}(\text{Global}) = \begin{pmatrix} 0.020 \\ 0.032 \\ 0.046 \\ 0.035 \\ 0.023 \\ 0.070 \\ 0.042 \\ 0.083 \\ 0.034 \\ 0.043 \\ 0.073 \\ 0.088 \\ 0.057 \\ 0.085 \\ 0.066 \\ 0.028 \\ 0.052 \\ 0.041 \\ 0.049 \\ 0.030 \end{pmatrix}$$

Step 8: Finally, the overall priorities of the alternative manufacturing systems reflecting the interrelationships within the measures are determined as follows:

$$W_{\text{alternatives}} = W_4 \text{ x } W_{\text{sub-measures}}(\text{Global}) = \begin{pmatrix} 0.270 \\ 0.325 \\ 0.210 \\ 0.195 \end{pmatrix}$$

From $W_{\text{alternatives}}$, it has been found that HFMS is the best manufacturing system with an overall priority of 0.325.

8.3.2 Prioritization of manufacturing systems with AHP

In this chapter, AHP has been used for prioritization of four types of manufacturing technologies and the selection of manufacturing system that is most suitable for Indian industries. Various steps of AHP are:

Step 1: First of all, the objective is determined, and the pertinent evaluation measure and sub-measures are identified similar to the ANP model as shown in Figure 8.1.

Step 2: The weights or priority vectors are calculated by using the pairwise comparison at each level in the hierarchy w.r.t the overall goal of the problem. The judgments are entered using the fundamental scale of the AHP (Saaty, 1980, 2000). Pairwise comparison of measures is done in similar way as shown in Table 8.2. Similarly, pairwise comparison of sub-measures is done as shown in Table 8.8- 8.11.

Table 8.8: Pairwise comparison of flexibility sub-measures

Sub-measures	TM	SUT	TOM	VP	SVW		Priority vectors
TM	1	3	2	3	2		0.362
SUT	1/3	1	1/3	2	1/3		0.105
TOM	1/2	3	1	1/3	1/2		0.134
VP	1/3	1/2	3	1	1/3		0.124
SVW	1/2	3	2	3	1		0.275

Table 8.9: Pairwise comparison of MHS sub-measures

Sub-measures	TMT	PIV	BM	CBV	FM		Priority vectors
TMT	1	3	1/2	1/3	1/4		0.113
PIV	1/3	1	1/3	2	1/3		0.101
BM	2	3	1	3	1/2		0.265
CBV	3	1/2	1/3	1	1/3		0.119
FM	4	3	2	3	1		0.402

Table 8.10: Pairwise comparison of performance sub-measures

Sub-measures	PT	MFT	NPP	LT	MS		Priority vectors
PT	1	3	2	3	2		0.364
MFT	1/3	1	1/2	1/2	2		0.124
NPP	1/2	2	1	1/3	2		0.164
LT	1/3	2	3	1	3		0.254
MS	1/2	1/2	1/2	1/3	1		0.094

Table 8.11: Pairwise comparison of fixture and pallet sub-measures

Sub-measures	FF	FST	CP	EPL	CF		Priority vectors
FF	1	3	3	3	2		0.383
FST	1/3	1	3	1/2	2		0.172
CP	1/3	1/3	1	1/3	1/2		0.078
EPL	1/3	2	3	1	3		0.247
CF	1/2	1/2	2	1/3	1		0.120

Step 3: Eigen values, consistency index and consistency ratio are determined.

Step 4: Global weights are determined to evaluate the normalized weights of the sub-measures. They are determined by multiplying the priority vectors of each measure with the priority vectors of the sub-measures that come under the corresponding measure. Sub-measures with their global weights are shown in Table 8.12.

Table 8.12: Global weight of sub-measures

Measures	**Priority vectors**	**Sub-measures**	**Priority vectors**	**Overall priority**
F	0.420	TM	0.362	0.152
		SUT	0.105	0.044
		TOM	0.134	0.056
		VP	0.124	0.052
		SVW	0.275	0.115

Measures	Priority vectors	Sub-measures	Priority vectors	Overall priority
MHS	0.190	TMT	0.113	0.021
		PIV	0.101	0.019
		BM	0.265	0.050
		CBV	0.119	0.023
		FM	0.402	0.076
P	0.269	PT	0.364	0.098
		MFT	0.124	0.033
		NPP	0.164	0.044
		LT	0.254	0.068
		MS	0.094	0.025
F and P	0.121	FF	0.383	0.046
		FST	0.172	0.021
		CP	0.078	0.009
		EPL	0.247	0.030
		CF	0.120	0.015

Step 5: To calculate the overall or composite score, rating for each sub-measure according to the facilities available in a particular manufacturing system is done. The pairwise comparison judgment matrix for the five-point rating scale is shown below in Table 8.13. The priority vectors corresponding to extremely important (EI), most important (MI), highly important (HI), important and necessary (I and N) and Important (I) are shown in the last column of Table 8.13. The global weight of each sub-measure is multiplied with its corresponding rating value for each alternative and summing over the sub-measure value for each alternative as shown in Table 8.14.

The manufacturing system whose overall or composite score come out to be the highest one is considered as the first preference.

Table 8.13: Pairwise comparison judgment matrix for the five-point rating scale

	EI	MI	HI	I and N	I	Priority vector
EI	1	3	5	7	9	0.513
MI	1/3	1	3	5	7	0.261
HI	1/5	1/3	1	3	5	0.219
I and N	1/7	1/5	1/3	1	3	0.063
I	1/9	1/7	1/5	1/3	1	0.034

From Table 8.14, the overall or composite score for HFMS come out to be the highest one, so it has been considered as the first preference.

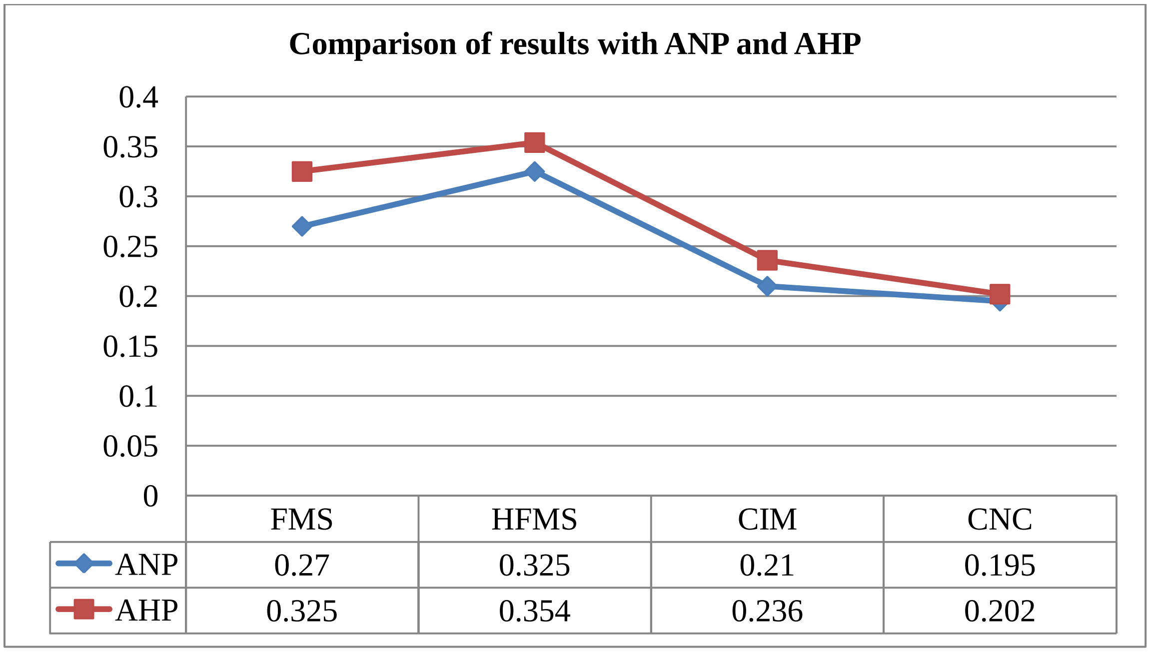
Table 8.14: Overall or composite scores of the alternatives

Sub-measures	**FMS**			**HFMS**			**CIM**			**CNC**		
	Rating	GW	Score	Rating	GW	Score	Rating	GW	Score	Rating	GW	Score
TM	0.513	0.152	0.078	0.513	0.152	0.078	0.261	0.152	0.040	0.261	0.152	0.040
SUT	0.261	0.044	0.012	0.261	0.044	0.012	0.261	0.044	0.012	0.261	0.044	0.012
TOM	0.261	0.056	0.015	0.261	0.056	0.015	0.261	0.056	0.015	0.261	0.056	0.015
VP	0.261	0.052	0.014	0.261	0.052	0.014	0.129	0.052	0.007	0.129	0.052	0.007
SVW	0.129	0.115	0.015	0.129	0.115	0.015	0.261	0.115	0.030	0.261	0.115	0.030
TMT	0.513	0.021	0.011	0.513	0.021	0.011	0.261	0.021	0.006	0.063	0.021	0.001
PIV	0.261	0.019	0.005	0.261	0.019	0.005	0.219	0.019	0.004	0.034	0.019	0.001
BM	0.513	0.050	0.026	0.513	0.050	0.026	0.261	0.050	0.013	0.063	0.050	0.003
CBV	0.261	0.023	0.006	0.261	0.023	0.006	0.129	0.023	0.003	0.034	0.023	0.008
FM	0.513	0.076	0.039	0.513	0.076	0.039	0.261	0.076	0.020	0.261	0.076	0.020
PT	0.261	0.098	0.026	0.261	0.098	0.026	0.129	0.098	0.013	0.129	0.098	0.013
MFT	0.129	0.033	0.004	0.129	0.033	0.004	0.261	0.033	0.009	0.261	0.033	0.009

Sub-measures	**FMS**			**HFMS**			**CIM**			**CNC**		
	Rating	GW	Score	Rating	GW	Score	Rating	GW	Score	Rating	GW	Score
NPP	0.261	0.044	0.012	0.261	0.044	0.012	0.261	0.044	0.012	0.129	0.044	0.006
LT	0.261	0.068	0.018	0.513	0.068	0.035	0.261	0.068	0.018	0.129	0.068	0.009
MS	0.129	0.025	0.003	0.129	0.025	0.003	0.261	0.025	0.007	0.261	0.025	0.007
FF	0.513	0.046	0.024	0.513	0.046	0.024	0.261	0.046	0.012	0.129	0.046	0.006
FST	0.261	0.021	0.005	0.261	0.021	0.005	0.261	0.021	0.005	0.261	0.021	0.005
CP	0.261	0.009	0.002	0.261	0.009	0.002	0.129	0.009	0.001	0.063	0.009	0.001
EPL	0.261	0.030	0.008	0.513	0.030	0.015	0.261	0.030	0.008	0.261	0.030	0.008
CF	0.261	0.015	0.004	0.513	0.015	0.007	0.261	0.015	0.004	0.261	0.015	0.004
Total			**0.325**			**0.354**			**0.236**			**0.202**
Normalizing			**0.32**			**0.35**			**0.24**			**0.20**

8.4 DISCUSSION AND CONCLUSION

In this study, most critical measures and sub-measures which could affect the overall efficiency of a manufacturing organization have been identified and analyzed for prioritization of alternatives (FMS, HFMS, CIM and CNC system), so that the management could take the decision which manufacturing system suits them the most. These measure and sub-measures have been identified through the literature review, questionnaire survey, and interactions with practicing managers and academicians. The present problem has been illustrated and compared by two multi-criteria decision methods, i.e., ANP and AHP.



	FMS	HFMS	CIM	CNC
ANP	0.27	0.325	0.21	0.195
AHP	0.325	0.354	0.236	0.202

Figure 8.2: Comparison of results with ANP and AHP

In ANP, the problem has been analyzed by assuming that there is no dependence among the measures. Prioritization of the alternatives with ANP approach is HFMS > FMS > CIM > CNC. When the same problem has been analyzed with the help of AHP, then HFMS come out to be the best alternative, with a composite score of 0.354. In AHP, when dependence among measures is assumed then, the overall score values of the alternatives changed. However, the prioritization of the alternatives remained same. The comparison of results obtained from the ANP and AHP approaches has been shown in Figure 8.2, in which HFMS comes out to be the best alternative by ANP and AHP. Hence, it is proposed that industries in the developing countries like India should adopt advanced manufacturing techniques but in the form which is best suited to their socio-economic systems.

Apart from a number of calculations involved in these approaches, they are simple to understand and intelligible enough to handle a large number of measures and sub-measures. The results obtained in this study can help the management in making strategic and tactical decisions for the improving the efficiency of a manufacturing system. In this chapter, HFMS has been proposed and justified for countries where sufficient manpower is available like India.

CHAPTER IX

STUDY OF ALTERNATE TECHNOLOGIES TO CNC IN FMS

9.1 INTRODUCTION

In today’s highly stressed and unstable environment, organizations are trying hard in an attempt to boost their capabilities, so that they could produce high-quality goods for their customers by improving the cost effectiveness of their operations (Kahrarian, 2014). New variety of products are pumped into the market by multi-national companies (MNCs). Only those products succeed that can adapt to market requirements in a short time (Stefanic et al., 2008). FMS is the best answer to such type of challenges.

A number of authors have discussed FMS control and simulation in their research work which reflects the application of new technologies and techniques like fuzzy logic, neural network expert systems, and artificial intelligence to FMS. There is very low industrial feasibility of their implementation because these control and simulation methodologies are so complex. The advancement of CNC machines provided the major technological foundation upon which early FMS versions were built. According to Overmars and Toncich (1994), a major factor behind this foundation was the growth and interfacing of CNC with CAD through the 1970s. Due to the capability of producing a variety of parts via reprogramming, CNC machine tools became a vital manufacturing method (Xu and Newman, 2006). As a result of this, CNC machine tools with multi-axes and multi-process workstation configurations were elaborated, to aid the high-speed machining of critical parts (Newman et al., 2008). But, in todays’ world of competitiveness, a number of challenges are faced by the industries such as rapidly changing demands of customers and frequent process modifications, etc., in which CNC machining industries are lacking to produce the scale of efficiencies desired to remain viable. Capital investments involved with CNC machine tools is also high. However, more innovative alternatives are provided by technological development in control system topologies used in other disciplines of engineering. They have significant potential and have not yet been fully explored. The new FMS structure is shown in Figure 9.1.

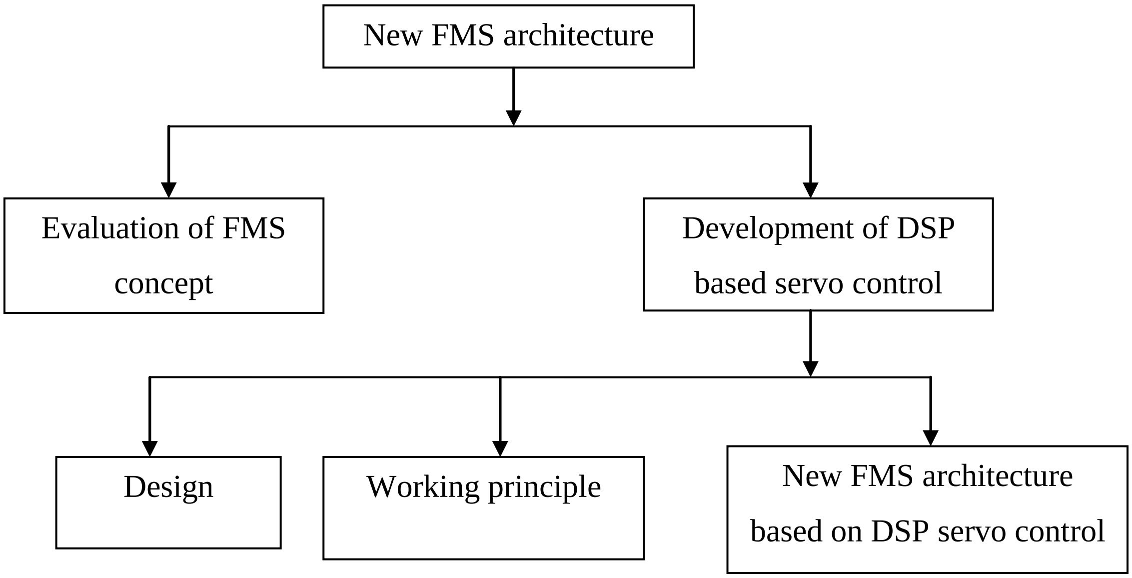


Figure 9.1: New FMS structure

The basic feature of FMS is its flexibility, so the main purpose of designing the new FMS architecture was to utilize techniques in order to develop easier and more efficient systems, i.e., an individual programmable axis. Overmars and Toncich (1994) proposed the application of new digital signal processors (DSP) servo control methodologies.

9.2 EVALUATION OF FMS CONCEPT AND PROBLEMS ASSOCIATED WITH TRADITIONAL FMS

Numerous authors have defined the FMS concept in the literature. Some of the FMS concepts defined by different authors are:

Browne et al. (1984) defined “FMS as an integrated, computer-controlled system of NC machine tools and automated material handling devices, designed to produce mid-volume and mid-variety of part styles simultaneously.” In this description of FMS, the NC/CNC machine was assumed as a basic and only unit of flexibility. The main purpose of designing of this new production technology was to achieve the efficiency of well-balanced machine paced transfer lines, at the same time utilizing the flexibility that job shops have, to machine various part styles simultaneously.

Toncich (1994) proposed that to achieve the flexibility in the production systems individual modules in the system should be able to act in response to changes in the part-mix. This can be attained by using fully programmable machining modules and flexible parts handling techniques.

Both the concepts are valid theoretically, but the main problem lies when they are applied practically in a real environment. According to Overmars and Toncich (1994) and Overmars and Toncich (1996), following problems arises in traditional FMS:

- When different devices such as CNCs, AGVs, and robots, etc. are integrated to perform different operations, they create artificial boundaries between groups of axes, which should not occur. Practically, they should be compatible with each other, so that any CNC machine tools can be used with any of the above devices without much difficulty.
- In traditional FMS, mostly CNC is used as basic machine tool, and robots and AGVs are used as material handling systems, so the extensive use of these devices again create the same problem of artificial boundaries between groups of axes.
- If the complex operation is performed at any one of the CNC machines in an FMS, it will increase the cycle time of that particular CNC machine which in turn lower the utilization of automatic MHS.
- If any CNC machine is used for performing simple operations, then it becomes difficult to justify the high cost involved with the fully programmable machine.

Therefore, to overcome these difficulties, use of DSP servo control methodologies as an alternative of CNC has been proposed.

9.3 DEVELOPMENT OF DSP BASED SERVO CONTROL

According to Brennan and Cortese (1991), the increasing availability of DSPs would lead to the development of more intelligent drive systems which would alter the basic structure of the industrial controller. Overmars and Toncich (1994) discussed how such intelligence could be incorporated into the servo drive control system. They proposed that the advancement in processor technologies and the cost reductions have enabled alternative FMS control architectures to be developed without the restrictions of ‘fixed machine controller boundaries.’ These new architectures called flexible numerical control (FNC) is based on the intelligent servo axes.

According to Overmars and Toncich (1994), “new FMS architecture can be defined as an integrated computer controlled production system in which processing stations are mounted on programmable axes, and additional programmable axes or a simple point to point transfer mechanisms can be used for the purpose of transporting and fixturing of material among different processing stations." The problems of artificial boundaries between a group of axes and costly interfaces do not occur in FNC. Therefore, it provides great flexibility and tighter control with much lower complexity per axis (Overmars and Toncich, 1996).

9.3.1 Design

The basic DSP servo control system has been shown in Figure 9.2. The heart of the system is the DSP. The axis control in a CNC machine tool is provided by CPU and here, the main purpose is to replace the CPU with an efficient DSP for each axis. The loading on the host and network is reduced by this system and more processing power is provided by the servo motors. The hardware of this system comprised of motor power drive system, encoder pulse counter, network interface and the DSP core. Overmars and Toncich (1994) stated that a number of features are required by a DSP-based servo controller to manage its local environment and communicate in real-time through a network.

The basic design requirements for DSP control of servo motors include (Overmars and Toncich, 1994):

- Sufficient drive power for the motor
- Counters for encoder feedback
- Processing resources to implement a software feedback algorithm (example, PID) within the DSP.
- A high-speed communications interface for interaction with a host (scheduler).

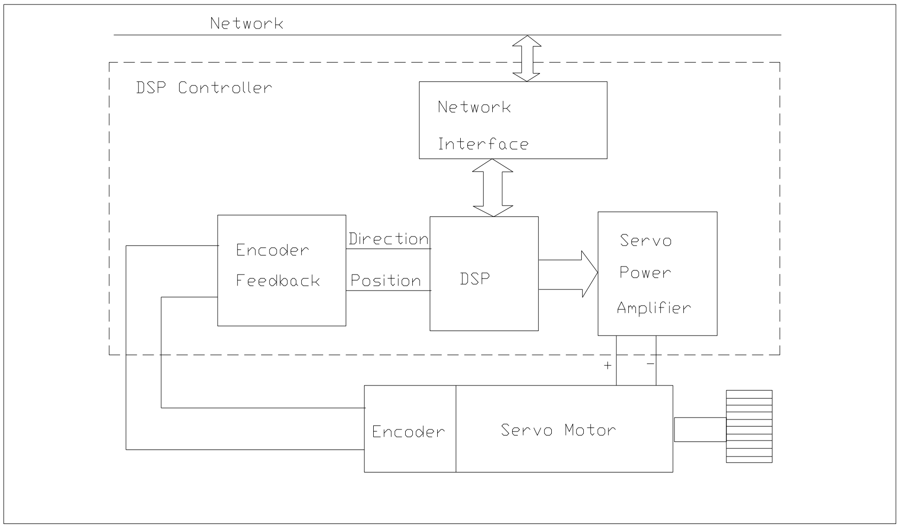


Figure: 9.2 DSP-based servo control (Overmars, 1993)

To get the actual servo motor drive, the pulse width modulation (PWM) technique or ‘H-Bridge drive’ is used as shown in Figure 9.3.

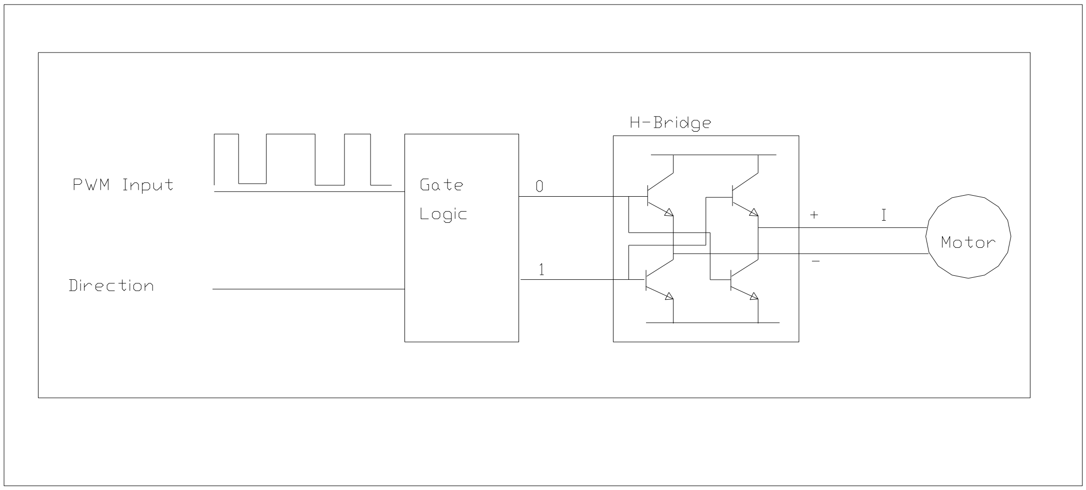


Figure 9.3: Using DSP control to drive DC motors through PWM technique (Overmars and Toncich, 1994)

A current proportional to a duty cycle is produced by the PWM technique. Here, the DSP is used to set and modify the PWM duty cycle, supply frequency and rotation direction. DSP modify duty cycle and rotation directions on the basis of feedback and also controls the position of servo motors. Pulse counters are used to fed the position feedback from the encoders and also gives direction information. Velocity is obtained by the differentiation of incremental changes in position, and double differentiation gives acceleration. By comparing between velocity and current PWM settings, torque is calculated by the DSP instantaneously.

9.3.2 Working Principle

The system with DSP technology has been shown in Figure 9.4. A host scheduler is used to control all the commands such as position, velocity and acceleration profiles or control strategies and then transmit it to the network. Here, the overall system control functions are executed by the host scheduler for the movement of a number of servo-driven axes. Now, the host scheduler works as a system management and passes commands and parameters to slave DSPs and scheduling events. This system permits each DSP to control its own local environment under the command of a host scheduler (Overmars and Toncich, 1996). Once these commands are received, servo controller is used to assure that the servo motors are driven to a position as required by a particular operation with the help of received control strategy. By utilizing DSP technology and advanced power electronics, these servo controllers can be made reasonably small and placed close to the relevant motor.

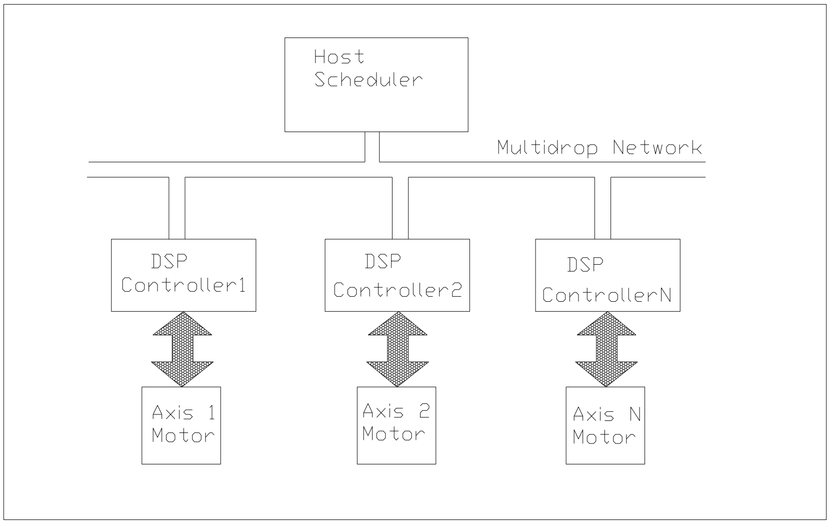


Figure 9.4: Implementation of a DSP system

9.3.3 A New FMS Architecture Based on DSP Servos

An FMS structure based on DSP servo-control system is shown in Figure 9.5 (Overmars and Toncich, 1994). In case of traditional dedicated in-line system, a number of standard (but relatively inflexible) machines with only one axis movement with a single or multi-spindle processing head are brought together and interconnected by a common part handling system such as conveyor system. Whenever re-tooling or repositioning of cutting heads is required, the system needs to be shutdown, to process the large batches of a limited range of part styles. In this way, flexibility is achieved in these systems but with a significant downtime between different part styles.

Although FMS can be used to produce a range of widely different part styles, high costs and complications related to fixturing and transportation of different part styles among the workstations, create severe limitations on real-time flexibility achieved. Overmars and Toncich (1994) proposed that by re-examining the limitations of dedicated systems, in integration with new servo-drive technologies, it may be possible to design simpler, flexible systems with sufficient functionality for the practical part varieties required by a manufacturer.

A number of features could be added in order to increase the flexibility of the existing system, without replacing the existing workstations with complete multi-axis CNC machine tools. According to Overmars and Toncich (1994), these features include:

- Programmable advance and retract of axes
- Programmable end-effector offset
- Programmable tool selection

A dedicated system in which a number of machines with limited degree of flexibility are arranged to produce a variety of part styles is shown in Figure 9.5. According to Overmars and Toncich (1994), Y station is an advance and retract machine with programmable Y movement, recognized through a DSP servo control. XY-station has two programmable, servo-driven axes.

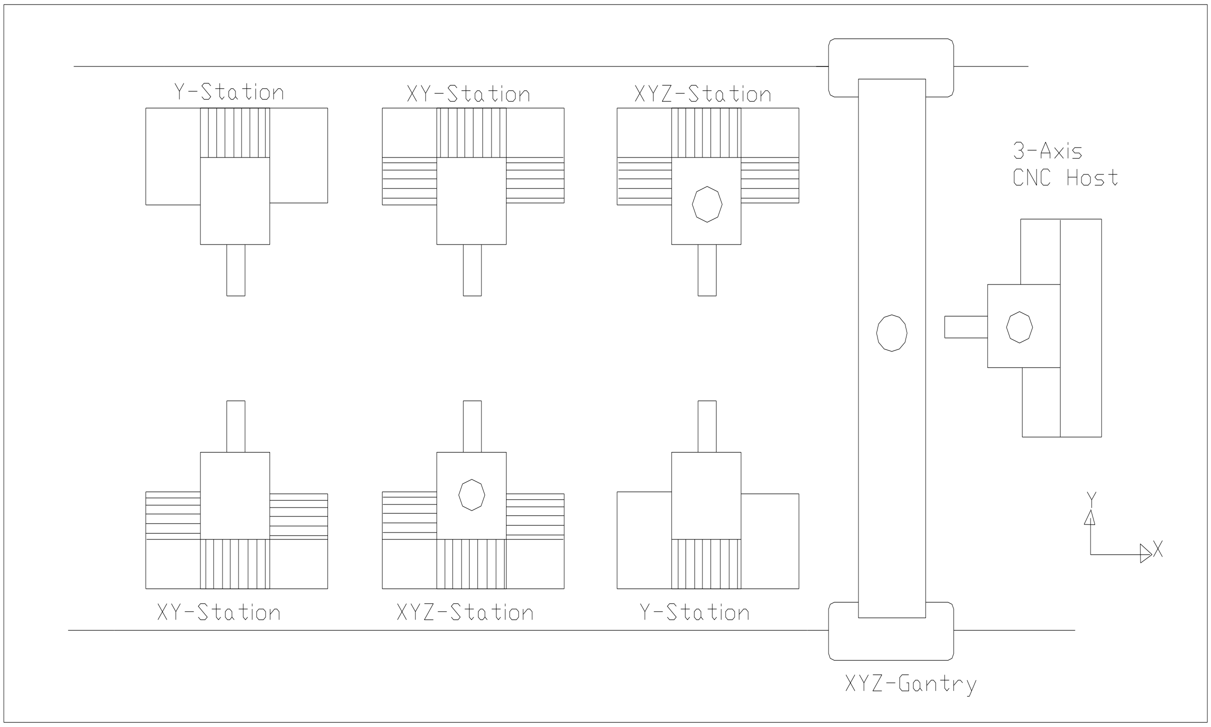


Figure 9.5: Example of a typical FMS under networked DSP control

The X movement can either provide a programmable offset axis for different part styles, or it can provide a programmable tool selection feature. The XYZ movement can provide two programmable offset axes and one programmable advance and retract axis. Apart from the traditional point-to-point conveyors and shuttles, there are transfer mechanisms such as X-transfer machine, XY-transfer machine or XYZ-transfer machines. As discussed above, in DSP servo control architectures, a host scheduler is used to control all programmable axes, i.e., a workstation networked to all active servo drives. The functions performed by the host controller would include the coordination and optimization of all programmable axis movements, minimization of interference between axis movements and scheduling of part transfer and resource.

In some cases, grouped axis control is needed. In those situations, a CNC system would need to be added in order to produce complex shapes and to provide a standard interface between CAD and CAM in the new architecture of FMS. Overmars and Toncich (1994) proposed that CNC incorporated within the new architecture of FMS should be an open architecture in order to serve the functions of grouped-axis machine control (local processing) and coordination of all other programmable axes (host scheduling) i.e., CNC machine will act as the host scheduler for the FMS as well as a machine controller to produce the complex shapes. In case, an open-structure CNC machine is not available or insufficient processing capacity exists, then a high-performance PC can be used to perform the functions of host scheduler.

So, in this way, a dedicated, in-line transfer machine system can be extended with the new architecture for FMS. In other words, a new architecture for FMS may be both financially and technically practical to provide a reasonable level of flexibility to high-volume production equipment.

9.4 BENEFITS OF DSP SERVO CONTROL TECHNOLOGY

According to Overmars and Toncich (1994), DSP servo control technology provides a number of potential benefits, as mentioned below:

- It provides higher level of integration so, the artificial boundaries between the group of axis are eliminated by the use of DSPs
- It provides the higher flexibility and better control because of its capability of individual axis control
- It provides the compactness as the high degree of integration provided by DSPs enables the smaller servo controllers to be implemented
- It reduces the requirement for complex wiring looms as the servo controller are placed close to the relevant motor
- The need for higher-level network interfaces, such as those between CNCs and robots is diminished.
- It provides intelligent closed-loop control and also minimizes the requirement for complex, high-cost monitoring of abnormality conditions.
- It provides more processing power and greater flexibility in a system at a better price/performance ratio than is available from CPUs
- It provides more reliability than CNC.

9.5 OPEN ARCHITECTURE CNC CONTROL

CNC machines were developed in the 1970s and this device replaced the NC with computers. The controller is the heart of CNC system consisting of software and hardware. Nowadays, conventional controller of CNC machines are found to be close in nature due to dependency on vendor specifications, i.e., they do not facilitate access to the inner features of the CNC controllers and axis control systems (Latif and Yusof, 2014). These systems are closed in both aspects hardware and software. According to Mori et al. (2001), CNC systems along with their controller are supplied by the vendors as a ‘black box’ which makes it difficult for the manufacturer to quickly develop and implement the custom control functions.

CNC system is demanded to have a modular structure and the ability of fast reconstruction in software and hardware to meet rapid development of technology, market and organizational structure in the production system (Erol et al., 2000; Bin et al., 2004). The challenges faced by CNC machining industry created a need for smarter, more flexible, modular and cost effective solutions and in order to overcome these shortcomings, open architecture controllers need to be developed. The aim of this technology is to develop the controllers independent from the manufactures technology, allowing the user to purchase hardware and software from different manufacturers and freely assemble the acquired piece of equipment (Asato et al., 2002).

A variety of open-architecture control systems are used in industries. But, within the scope of present research, only open architecture CNC control system is considered here. Since open architecture CNC control systems have value added advantages over the other control systems in terms of flexibility of customization and ongoing upgrades features for its end users which they needed for maximizing the lean performance and continuous process improvement. The enhanced performance and improved processes result in high profits and increased lifetime ROI. An Open Architecture Controller (OAC) should be flexible in hardware as well as in software for all control levels (Wright et al., 1996).

Capturing and analyzing data related to the processing and cutting operation is one of the vital factors for improving the process. To improve the performance of CNC machine tool, control and upgradation of different inputs are required in order to improve the manufacturing or cutting capabilities of the machine. A Windows-based, open architecture control system offers various features such as connectivity, traceability, and adaptability which empower end users in continuously improving processes, implementing management control, reducing costs and improving quality.

Open architecture is based on a philosophy of removing the barriers, limitations and planned obsolescence obtruded by proprietary CNC control systems. According to Yamazaki (1996), the open architecture CNC should have the characteristics of transparency, transportability, transplantability, reconfigurability, evolutionary and liveliness. According to Asato et al. (2002), “open architecture CNC control is considered as a promising technology in the area of industrial automation, allowing the integration of the equipment, a more friendly interface in the configuration, machine tool communication and modernization.” Benefits of using an open architecture when developing new CNC controllers include lower-cost electronics and higher performance computers (Pietrusewicz, 2008).

9.5.1 THe Intelligent Numerical Control (THINC)

At International Manufacturing Technology Show (IMTS), 2004 machine tool vendor Okuma America launched its new vision of control hardware and software under the name THINC, a forward-looking vision of an open architecture PC control. THINC is the industry's first open architecture CNC control that grows with emerging technology even after a machine is on the factory floor, so this extends the life of CNC machine significantly. Okuma (2004) believes that the design, implementation, and use of CNC system have been out of date at present and the time for fundamental change has come. THINC not only make a smart decision without human intervention but also keep increasing the functions automatically during the application of machine tools and will be more adaptive to new environment change, more tolerance, more easy programming and using. By using THINC, the machine will lead to higher production efficiency without human intervention (Dai and Wang, 2015).

The THINC open architecture control grows with technology, permitting it to adapt to varying customer demands (Okuma, 2004). THINC develops a connection between the machine tool, the human resource and the information components, and improve the capability of the machine tool to produce workparts by interfacing, via ethernet cable or USB connection, with peripheral equipment, accessories, and information sources. The features such as the ease of connectivity, the capability to read and process information, reduces the requirement for surplus inputs, minimizes human interference and gives security controls.

THINC comprised of a single processor, so it can be interchanged easily to remain technologically updated and its memory can be upgraded independently by the end user. Therefore, minimizing the costly memory options and giving the flexibility to utilize any preferred existing technology. According to Okuma (2004), with the THINC CNC control, it is feasible to trace things such as the origin of raw materials, what type of tool was utilized to perform the operation, which worker was operating the machine tool, the time at which the parts were manufactured, on which machine tool the parts were manufactured, etc. and the THINC CNC control can flexibly adapt to various manufacturing environments and formats. Monitoring and measurement through the CNC control provide end users with robust, adaptable tools that reduce waste and downtime.

9.6 OPEN NUMERICAL CONTROL SYSTEM (ONCS)

According to Yuhai et al. (2010), the ONCS has complete functions and excellent performance and can meet the request of modern numerical control machine tool for the open numerical control system. In the present scenario, a kind of numerical control is required to develop, which must be expanded easily, its functions are flexible and opened for the user. This kind of numerical control is called ONCS. The open level of ONCS can be measured by some features such as interchangeability, retractability, interoperability, portability, and reconfiguration. According to Yuan et al. (2013), there are three paths to realize open numerical control system. These are as follows:

- Personal Computer (PC) with the special board of numerical control (NC): The openness of this kind of NC is confined to computer only, but the part of professional NC is in enclosing state.
- PC with programmable motion controller: This kind of open NC is constructed on open programmable motion controller and industrial personal computer (IPC). The motion controller, which is the standard plug-in unit of PC, is the kernel of the open NC system. Managing functions are administrated by PC, logic and motion control of the machine tool are administrated by the motion controller. It has the openness of master and slave, and its development cost is low.
- Only PC: This kind of open NC is only constructed on PC. I/O board is usually inserted into the expansion slot of PC and connected with servo modules, I/O signals, and other

hardware modules. This pattern of open NC is provided to the users for maximum flexibility and options, but its development cost is higher, and its development cycle is longer.

Comparing to the three models, the second model which is ‘PC with programmable motion controller’ is used to construct open numerical control and the performance of this kind of ONCS can be ensured. With the help of PC technology, the kind of open NC system can conveniently realize the graphical interface, network communications, strong versatility of software and good openness. Therefore, it is currently a feasible mode to develop the open numerical control system based on collaborative design and development.

9.6.1 ONC System Architecture

According to Yuhai et al. (2010), the ONC system consists of application software and system platform (ONC-API, system software and system hardware). Control system consisted of application software, ONC-API and system software as shown in Figure 9.6.

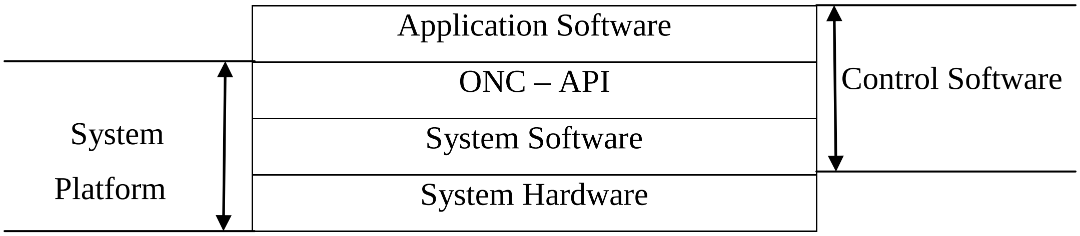


Figure 9.6: ONC system architecture

Application software includes specifying functions which were realized by corresponding function modules connected to the standard interface, such as motion preparation (MP), motion control (MC), axis control (AC), logic control (LC), input/output drive (IODrv), HMI, system configure, etc. These function modules can be run on the different system platform that obeys requirement of the ONC architecture. System platform, constructed according to the opening requirement, includes system hardware, system software and application program interface as shown in Figure 9.7. ONC system consists of application software, system software, and system hardware. The hardware platform is the physical body to realize system functions. Functions of this ONC system are divided into hard real-time tasks realized by IPC and soft real-time tasks realized by PMAC. The ONCS developed using IPC and PMAC motion control card has features like a shorter cycle, lower cost, portability, extendibility, interoperability, and scalability, etc. So, hardware platform consisted of IPC, PMAC2A-PC104 and PMAC's options. The software of ONC system is more important and consisted of a basic platform, application platform, and application program. The basic platform includes operation system, communication system, and graphic system, etc. Application platform includes discrete I/O control API, sensor API and position controller API, etc. The application program includes process control, HMI and support an environment of system integration and configure.

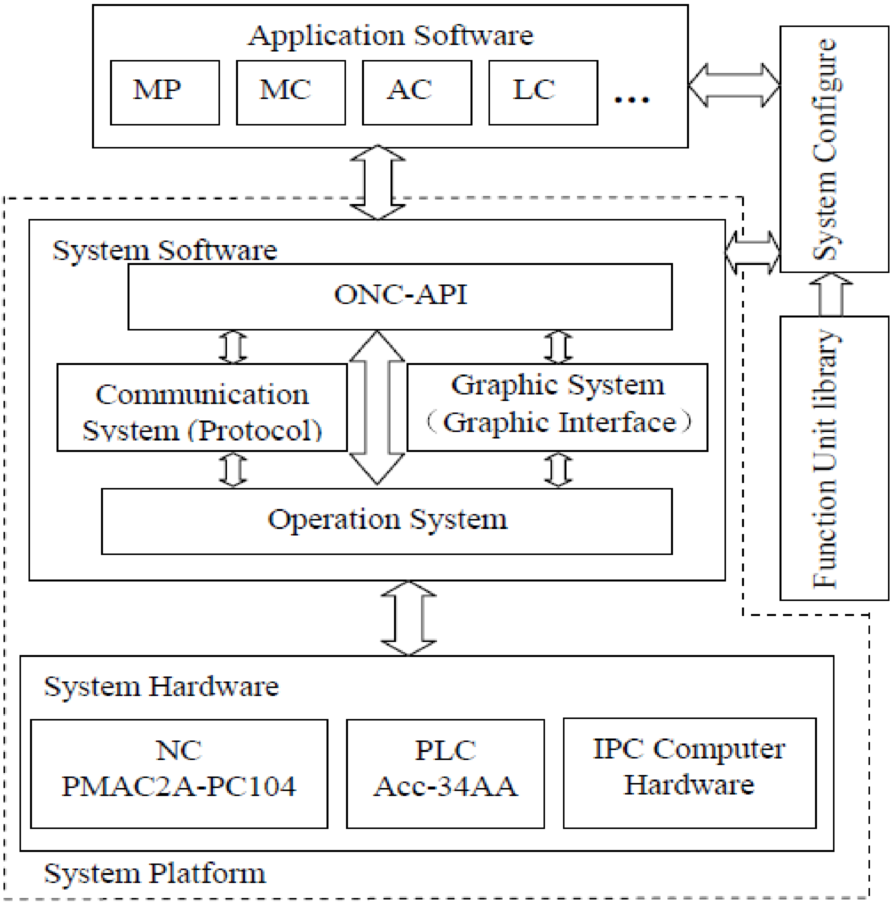


Figure 9.7: Diagram of ONC system (Yuhai et al., 2010)

This ONCS is used by the industries as it provides more flexibility and can be expanded easily according to the requirements of the fluctuating market demands. It has many more advantages such as high open flexibility, low cost, easy updating and expanding, little investing risk, including the newest technology of PC software and hardware, etc.

9.7 DISCUSSION AND CONCLUSION

In this chapter, some alternate technologies other than CNC i.e. DSP servo control technology, open architecture CNC, and ONCS have been discussed. The new definition of an FMS i.e., FNC discussed in this chapter provides scope for more effective systems to be developed and opens up a new range of research possibilities. A number of potential advantages of using FNC in flexible manufacturing have been discussed here including control of individual axis and elimination of artificial axis boundaries and costly interfaces. Limitations of traditional FMS, design and working principle of DSP servo control technology have also been discussed in this chapter.

Open architecture CNC control systems which are more flexible, expandable and user-friendly as compared to traditional CNC systems and THINC software have also been discussed.

Advantages of using ONCS and architecture along with the paths to realize ONCS has been discussed. Hardware and software platforms are also presented.

CHAPTER X

SYNTHESIS OF RESEARCH WORK

10.1 INTRODUCTION

In the present market scenario, an FMS has been addressed as the ultimate weapon for enhancing the production and rivalry of the organization. The rising trend towards globalization requires these manufacturing organizations to expand their actions such that it can accommodate the challenges of the marketplace to survive and grow. The technological advancement and present uncertain market demands have made it almost mandatory to several industries to switch over to FMSs. But the adoption of FMS is a complicated task as it involves huge capital investments. The decisions regarding these investments have become crucial for the survival and growth of manufacturing industries. There are various factors/measures which affect the performance of FMS and needs to be managed for the successful implementation of the FMS. For this purpose different type of measures are analyzed. In this chapter, synthesis of research work which has been carried out in previous chapters has been discussed.

10.2 SYNTHESIS OF RESEARCH WORK

Research reported in this thesis concerns the investigation of some selected issues related to the design and development of FMS in the context of Indian manufacturing industries. The research was carried out with objectives mentioned in chapter 1. The achieved objectives are as follows:

- The literature existing on some selected issues related to the design and development of FMS has been studied. Various factors affecting the different issues of FMS have been identified.
- The perception of Indian manufacturing industries towards different issues and factors related to FMS have been analyzed through a questionnaire-based survey.
- Different factors affecting the machine, product and routing flexibilities have been identified, and W-ISM based framework has been developed for understanding the key factors affecting flexibilities.
- Different performance measures have been identified, quantified and prioritized with the GTA. SAW and WPM integrated with AHP have also been used for prioritization of

different performance measures.

- Various aspects related to AGVs have been studied. Various factors affecting the design and development of AGVs are identified, and AGV's path layout has been optimized with the help of 0-1 Linear Integer Programming.
- Various aspects related to flexible fixture and pallets have been studied. A case study has been discussed and a design of pneumatically controlled flexible fixture with pallet has been proposed.
- With the help of AHP and ANP techniques, a comparative study has been done to select the best manufacturing system.
- Different technologies other CNC in design and development of FMS have been studied.

In achieving the above objectives, the methodologies used in the present research are shown in Table 10.1 and integration of these methodologies is shown in Figure 10.1.

The studies conducted in this research have been explained below:

An extensive literature review was carried out regarding the different issues related to the design, planning, operational, flexibility, performance, flexible fixture and pallets, MHS and other variables in design and development of FMS reported in Chapter II. A lot of research papers were studied regarding these issues. In Chapter III, the perception of Indian manufacturing industries towards different issues related to design and development of FMS have been presented. On the basis of results of the survey, different factors/measures were segregated and ranked which provided the basis for the development of model by W-ISM technique. In Chapter IV, W-ISM based framework has been developed on the basis of factors affecting the machine, product and routing flexibilities. The model shows the inter-relationship between these factors and their respective levels. These factors have been characterized according to their driving power and dependence power. EI has also been computed to find out the influence of different factors. Chapter V presents the development of GTA based framework for the quantitative analysis of performance measures identified through literature review and questionnaire-based survey. This study proposed a numeric value known as the index of performance, which can be utilized by the industrial managers to quantify the performance measures for improvement. SAW and WPM integrated with AHP have also been used quantitative analysis and for prioritization of performance measures.

Table 10.1: Methodologies used in the research

Objectives	Methodology used	Study No.
To identify various factors/measures related to the selected issues in the design and development of FMS	Literature review and expert opinion	1
To examine the perception of Indian manufacturing industries towards various issues related to design and development of FMS	Questionnaire-based survey	2
Analysis of the factors affecting machine, product and routing flexibilities in FMS	Weighted Interpretive Structural Modeling technique	3
Prioritization of different performance measures of FMS	Graph Theoretic Approach, Simple Additive Weighting, Weighted Product Method, Analytic Hierarchy Process	4
Optimization of AGV's path layout in FMS	0-1 Linear Integer Programming	5
Comparative study and prioritization of the manufacturing systems	Analytic Network Process and Analytic Hierarchy Process	6

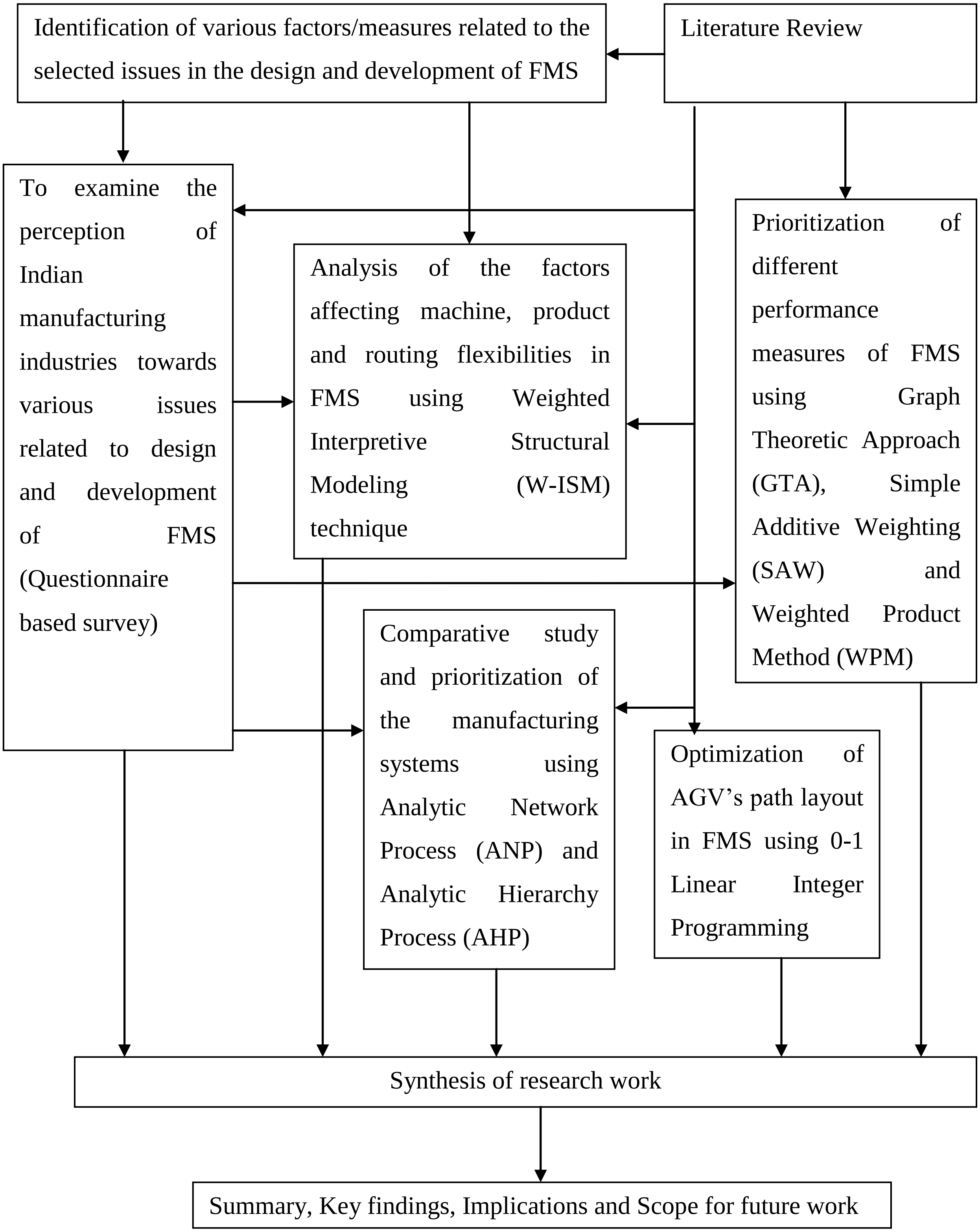


Figure 10.1: Integration of methodologies used in the research

Operational measures have been found with the highest composite score and IOP value, so management should focus on sub-measures falling under this category. The fuzzy logic used to change the qualitative measures into the quantitative measures has also been discussed. For the analysis, different performance measures were categorized into five groups: measures related to finance, measures related to customers, measures related to internal business, measures related to innovation and knowledge and operational measures. Development of 0-1 linear integer programming for optimization of AGV's path layout has been presented in Chapter VI. Various aspects related to AGVs have been discussed and various factors affecting the design and development of AGVs have also been identified through literature review, experts opinion and questionnaire-based survey. Review on various aspects related to flexible fixtures and pallets, their classification and CAFD along with some intelligent methods has been presented in Chapter VII. A case study has been discussed, and a design of pneumatically controlled flexible fixture with pallet has also been proposed in this chapter. In Chapter VIII, ANP and AHP based models have been developed for the comparative study and prioritization of different manufacturing systems. In this chapter, HFMS has been found the first preference among FMS, CIM and CNC systems. Study of alternate technologies other than CNC has been carried out in Chapter IX.

10.3 CONCLUSION

This chapter presents the synthesis of research work presented in this thesis. A diagram is presented to demonstrate the integration of different methodologies used in this research. Further, summary, conclusion, key findings, implications and scope for future work have been presented in the next chapter.

CHAPTER XI

SUMMARY, KEY FINDINGS, IMPLICATIONS AND SCOPE FOR FUTURE WORK

11.1 INTRODUCTION

Global competitions, advancements in technology and ever changing demands have made the manufacturing companies to realize the importance of an FMS (Raj et al., 2007a). A high degree of flexibility as well as ability to reconfigure operations for new demands are required for meeting the customers' needs and demands. All these requirements are forcing the manufacturing companies to adopt FMS. Although various issues related to FMS have been extensively explored during the past few decades by numerous researchers in their literature yet the adoption and implementation are still considered as a difficult task. This is due to the gap existing between the theoretical research for the design and development of FMS and practical expectations and real-life complexities of manufacturing industries. Low acceptance of FMS in developing country like India, has motivated the researchers to pursue research by exploring and analyzing the various issues in the design and development of FMS.

11.2 SUMMARY OF THE RESEARCH WORK

In this section, the summary of the research work done in achieving the research objectives is presented. The main work undertaken in this research includes the following:

- An extensive literature review was conducted to identify the gaps and some relevant issues in the field of design and development of FMS.
- On the basis of literature review and discussion with the experts both from industry and academia, a questionnaire was designed to collect the responses from different manufacturing experts based on their opinion. The responses obtained from the questionnaire based survey helped to understand the impact of various factors/measures in FMS and the inclination of the Indian industries towards adoption and implementation of FMS.
- Different issues related to design and development of FMS which have been considered in questionnaire includes factors affecting machine, product and routing flexibilities,

factors affecting the design and implementation of AGVs, factors affecting the performance of FMS, factors affecting the design and development of flexible fixture and pallets.

- The responses were analyzed and later used in achieving different research objectives with the help of different methodologies.
- W-ISM technique including ISM technique, MICMAC analysis, and EI have been used to analyze the various factors affecting machine, product and routing flexibilities to find out their driving and dependence powers. EI has been evaluated to find out the impact of each factor in FMS.
- GTA, SAW and WPM approaches have been used for quantifying the different factors affecting the performance of FMS.
- Various aspects related to AGVs such as guidance system, control systems, dispatching methods, safety aspects have been studied, and various factors affecting the design and development of AGVs have been identified. 0-1 linear integer programming has been used to find out the optimized path layout of AGVs in FMS.
- A case study has been discussed, and a design of pneumatically controlled flexible fixture with pallet has been proposed as per the requirement of the customer to handle a variety of workpiece configurations.
- ANP and AHP approaches have been used to find out the best manufacturing system by analyzing different factors.
- Technologies other than CNC in the design and development of FMS have been studied.

11.3 MAJOR CONTRIBUTIONS OF THE RESEARCH

The major contributions made through this research are:

- The present research provides a comprehensive review of the literature and identifies contemporary issues related to design and development of FMS in Indian manufacturing industries.
- The inclination of Indian manufacturing industries towards different issues and factors related to FMS has been found out.
- Various measures related to the machine, product and routing flexibilities are identified, and their drive and dependence power have been analyzed to identify the most significant

key factors/measures affecting different flexibilities.

- Various issues related to AGVs have been analyzed. Design and development of AGVs are affected by various factors, these factors have been identified and analyzed. The shortest possible path has been determined for a particular case for fulfilling the requirements of different machines in FMS.
- Various factors affecting the performance of the FMS have been identified and analyzed.
- IOP has been evaluated to quantify the various performance measures related to FMS. The performance index of any manufacturing industry can be determined with the help of this IOP.
- Prioritization of different performance measures has been done with the help of GTA, SAW and WPM approaches.
- Various aspects related to flexible fixture and pallets have been analyzed. A case study has been discussed, and designing of a pneumatically control flexible fixture with pallet has been proposed which can handle a variety of parts with different shape and sizes with minor changes in it for performing different operations on drilling heads.
- A comparative study of various factors in different manufacturing systems has been done and among all these manufacturing systems, the best manufacturing system has been found out.
- At last, some alternate technologies other than CNC in design and development of FMS have been studied.

11.4 KEY FINDINGS OF THE RESEARCH

The key findings emerge from this research are as follows:

- The levels of different factors affecting machine, product and routing flexibilities have been identified by ISM model.
- Skills and versatility of workers, type of machine, design changes required in the product and maximum number of routes available have strong driving power and weak dependency on other factors. They are considered as the ‘key factors’ affecting the flexibility of FMS.
- Setup or changeover time, tool changing time of the machine and type of operation to be done on the machine, these factors are weak drivers but strongly depend on one another.

- Based on the responses obtained through questionnaire survey on various factors affecting flexibilities, EI has been evaluated which has been found 7.0569 and maximum value can reach up to 8.7381. From this EI, it has been observed that organisations are doing quite well in terms of setup time, tool magazine, skills and versatility of workers, types of machine, variety of parts to be handled by machine, space availability, tool changing time and design changes in product, however, there is need for improvement in area of flexibility of MHS, number of routes available, types of operations to be done on machine and offline part programming preparation facility related problems for dealing well with the factors affecting flexibility.
- Different performance measures have been categorized into five groups: performance measures related to finance, measures related to customers', measures related to internal business, measures related to innovation and knowledge and operational measures. Their IOP is represented by single numerical index through GTA approach. Ranking or prioritization done with the help of GTA approach reveals that operational measures have highest IOP. Therefore, these are the most significant measures affecting the performance of FMS, so management should focus on these measures. By evaluating the IOP value for different organizations, their performance can be compared.
- Prioritization of same performance measures has been done with the help of SAW and WPM which have been integrated with AHP to find out the weights of performance measures and these weights have been used later in SAW and WPM methods. Fuzzy logic has been used to change the qualitative measures into the quantitative measures. Same ranking/prioritization of performance measures have been obtained with SAW and WPM methodologies as obtained with GTA, so ranking of these measures have been verified with SAW and WPM approaches.
- Optimized path layout of AGVs has been found with the help of 0-1 linear integer programming by using a simple example consisting of only four cells for conceptual clarification and real-time implementation in FMS environment. The procedure described in this research can be easily extended to more typical and more complex layouts.
- A case study has been studied in which customer requirement was a pneumatically operated flexible fixture with pallet for holding a variety of workpart configurations for drilling machines so, as per the customer requirement a design of pneumatically operated

fixture has been proposed which can handle a variety of parts with different shape and sizes with minor changes in it for performing different operations on drilling heads.

- ANP and AHP techniques have been used to rank or prioritize the four alternatives, i.e., CNC, FMS, HFMS and CIM systems by analyzing the weights of measures and their sub-measures. Measures used in the present research which affects the four alternatives are: flexibility, MHS, performance and fixture and pallets. Each measure has five sub-measures. After analyzing the measures and sub-measures for all four alternatives through AHP and ANP, HFMS has been found out the best manufacturing system in developing countries like India where labour is very cheap and easily available.
- DSP servo control methodologies and open architecture CNC have been studied as an alternate technology other than CNC in the design and development of FMS.

11.5 IMPLICATIONS OF THE RESEARCH

The present research has strong implications for researchers as well as manufacturing managers as discussed below:

Implications for researchers: Various factors/measures related to some selected issues have been identified and discussed in the present research. The researchers may be encouraged to identify some other issues, which may be notable in addressing these factors. Literature gaps identified on various issues related to FMS will be helpful to researchers in carrying out future research. The questionnaire presented in this research can be used as an instrument to carry out further research in the field of FMS. GTA approach and index calculations may motivate the researchers and academicians to develop the similar framework for other measures or issues. DSP servo control technology, discussed in the present research will be helpful to researchers in carrying out future research.

Implications for managers: The manufacturing managers can get an insight of these factors/measures and understand their relative significance and interdependencies and try to overcome these factors. The GTA, SAW and WPM models discussed here are effective tools for evaluation, comparison, and ranking of FMS performance. AHP and ANP approaches help to adopt the best manufacturing system by analyzing different factors. ISM methodology helps to strengthen the realistic views of manufacturing managers and provides a clear portrait about the impact of different factors. In this way, various factors can be recognized and dealt with utmost care. From the present research, the management can approach better strategies and guidelines for taking various decisions related to design and development of FMS. 0-1 linear programming discussed in this research will help the managers to optimize the path layouts of AGVs.

11.6 LIMITATIONS AND SCOPE FOR FUTURE WORK

A lot of efforts have been put in this research work to identify and analyze different issues related to design and development of FMS, but it has some limitations also. In this section, these limitations have been identified, and some suggestions for future research have been offered. The identified limitations of this research work are:

- All issues related to design and development of FMS are not considered in the present research, only some selected issues related to FMS are identified and analyzed for research.
- FMS performance is expressed in terms of an index value. This index value depends on the inheritance of main measures which further depends on their sub-measures and all these depend on the expert's opinion. Therefore, a suitable combination of measures and their sub-measures should be selected for evaluating the FMS performance.
- Pneumatic actuators are not so suitable for accurate ultra-precision positioning. Proposed design of flexible fixture can hold the workpieces upto a particular size.
- This research was conducted specially for Indian manufacturing industries, the outcomes of this research may differ slightly in other countries.

However, this research has a strategic effect on the design and development of FMS, some more work can be done in future, and the present research can be extended to the following directions:

- The ISM model developed in this research work can be validated by using structural equation modeling (SEM). SEM also known as linear structural relationship approach, is capable of testing the validity of such hypothetical models.
- W-ISM approach can be further extended to fuzzy weighted interpretive structural modeling (F-WISM), and total weighted interpretive structural modeling (T-WISM) approaches.
- In future, this research can be extended in designing other evaluation instruments which can identify performance measures specific to a particular type of domain.

- AGV path layout optimized with the help of 0-1 linear integer programming. The results can be verified by simulating the entire problem. The simulation would take into account the travel of unloaded vehicles, buffering, congestion and other control aspects, it would give a complete picture of the system.
- In future, an attractive field for research is fixture design in Micro and Nano-machining, because nanometric machining has a very different physics from conventional machining w.r.t physical properties, material, and the manufacturing process.
- Only a few literatures are available on welding fixture research, almost all the literature are focused on machining fixtures field. Very few artificial intelligence techniques carry out all the four steps of fixture design. More attention should be paid to these issues.
- Research on the use of intelligent online control methods to adjust the fixturing forces and contacts can be done.
- New technologies other than CNC in the design and development of FMS can be explored.

11.7 CONCLUSION

In the present research, some selected issues related to design and development of FMS have been discussed. The research objectives: identification and study of different variables affecting machine, product and routing flexibilities of FMS, study and development of different performance measurement models for FMS, design and development of industry based optimization technique for AGVs path layouts, design and development of flexible fixture with pallet for handling a variety of parts and study of the alternate technologies other than CNC system have been addressed here. Some literature gaps related to these issues have been identified. A questionnaire was prepared, and survey of Indian manufacturing industries was done to know the importance of various factors based on the opinion of different respondents.

Based on the developed W-ISM framework, skills and versatility of workers, type of machine, design changes required in the product and maximum number of routes available have strong driving power and weak dependency on other factors. They are considered as the ‘key factors’ affecting the flexibility of FMS. Setup or changeover time, tool changing time of the machine and type of operation to be done on the machine, these factors are weak drivers but strongly depend on one another. On the basis of EI, there is a need for improvement in the area of flexibility of MHS, number of routes available, types of operations to be done on the machine and offline part programming preparation facility related problems for dealing well with the factors affecting flexibility.

GTA, SAW and WPM frameworks have been developed for quantification and ranking of different performance measures, and IOP has been evaluated. With the help of this IOP, management can take the decisions regarding the improvements needed in different areas related to these measures to enhance the performance of FMS. GTA, SAW and WPM methodologies reveal that the operational measures are the most influencing measures affecting the FMS performance. These methodologies are effective tools for evaluation, comparison, and ranking of FMS performance.

Various aspects related to AGVs have been discussed such as guidance system, control system, vehicle dispatching method, and safety systems. 0-1 linear integer programming model has been developed with the objective of minimizing the total distance travelled by individual loaded AGV's. The procedure discussed here can help the management in making strategic and tactical decisions related to scheduling and path layout improvement for improving the efficiency and performance of a manufacturing system.

Various aspects related to flexible fixture and pallets have been discussed. A case study has been discussed, and a design of pneumatically operated flexible fixture with pallet has been proposed to handle a variety of workpieces with different shape and sizes with minor changes in it on drilling heads. The proposed fixture can be used in any manufacturing industry which is dealing with different drilling operations.

ANP and AHP based frameworks have been developed to find out the best manufacturing system among the FMS, HFMS, CIM and CNC by analyzing different measures related to flexibility, performance, MHS and fixture and pallets. ANP and AHP methodologies reveal that the HFMS is the best alternative specially for Indian manufacturing industries where labour is very cheap and easily available. Keeping in view the availability of cheap labours in developing country like India, high-cost MHSs like AGVs and robots can be replaced with human labours if required. In such cases, HFMS comes out to be the best option where work can be done by human labour who are easily available and have sufficient flexibility.

At last, some alternate technologies other than CNC such as DSP servo control methodology and open architecture CNC have been discussed.

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APPENDIX A1

QUESTIONNAIRE

Research Supervisor: Dr. Tilak Raj, YMCA University, Faridabad

Subject: Survey on different issues related to Flexible Manufacturing System

Dear Sir/Mam,

Flexible Manufacturing System (FMS) provides an opportunity to the firm to meet the challenges imposed by international competition, ever changing customer demands, rapid delivery to market and advancement in technology. As a part of Ph.D research, a survey of Indian industries is being conducted on different issues related to FMS such as various factors affecting the machine, product, routing flexibilities, the design and installation of AGV, the performance of FMS, and the design and development of flexible fixtures and pallets. To make it possible, the industry and academia must share their views. Your feedback in this regard will become a significant input to this study. I request you to spare your valuable time in responding to the enclosed questionnaire which has been divided into the following two sections:

Section 1: Organization profile

Section 2: Issues related to FMS

I would be grateful if you kindly answer the questions and send it at the earliest. The objective of the survey is purely research and academia in value. Therefore, all responses will be kept strictly confidential and will be used only for this academic work.

Thanks with warm regards,

Yours Sincerely,

SUMAN GOTHWAL
Research Scholar

QUESTIONNAIRE

Section 1: Organization profile

1. (A) Name of organization…………………………………….

(B) Type of business………………………………………….

2. Please indicate the number of employees at your organization:

(A) Less than 100 [ ] (B) 101 to 500 [ ] (C) 501 to 1000 [ ]

(D) 1001 to 2000 [ ] (E) More than 2000 [ ]

3. Please indicate the total turnover of your organization in Crores of Rs.:

(A) Less than 10 [ ] (B) 10 to 50 [ ] (C) 50 to 100 [ ]

(D) 100 to 500 [ ] (E) 500 to 1000 [ ] (F) More than 1000 [ ]

4. Please indicate the number of models of your product (variety) being manufactured:

(A) 1-5 [ ] (B) 6-10 [ ] (C) 11-20 [ ] (D) More than 20 [ ]

6. Please indicate the total percentage of components being manufactured inside the plant

(A) Less than 25 [ ] (B) 25-50 [ ] (C) 50-75 [ ] (D) 75-90 [ ] (E) 90-100 [ ]

7. The current productivity level in terms of units per man per day is approximately:

(A) Less than 10 [ ] (B) 10-25 [ ] (C) 25-50 [ ] (D) 50-100 [ ] (E) More than 100 [ ]

Section 2: Response of different issues related to Flexible Manufacturing System

8. Please rank the following factors affecting the machine, routing and product flexibilities in Flexible Manufacturing System:

	Factors affecting Machine Flexibility	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
		1	**2**	**3**	**4**	**5**
A	Types of machine	☐	☐	☐	☐	☐
B	Maximum number of tools available	☐	☐	☐	☐	☐
C	Maximum number of operation available	☐	☐	☐	☐	☐
D	Tool magazine or tool turret capacity	☐	☐	☐	☐	☐
E	Tool changing time	☐	☐	☐	☐	☐
F	Type of operations to be done on machine	☐	☐	☐	☐	☐
G	Variety of parts to be handled by the machine	☐	☐	☐	☐	☐
H	Skills and versatility of workers	☐	☐	☐	☐	☐
I	Setup or changeover time	☐	☐	☐	☐	☐

	Factors affecting Routing Flexibility	**Very Low** **1**	**Low** **2**	**Moderate** **3**	**High** **4**	**Very High** **5**
A	Number of machines available in the system	☐	☐	☐	☐	☐
B	Maximum number of routes available	☐	☐	☐	☐	☐
C	Similarity of workstations	☐	☐	☐	☐	☐
D	Common tooling available	☐	☐	☐	☐	☐
E	Space availability	☐	☐	☐	☐	☐
F	Availability of technical know how	☐	☐	☐	☐	☐
G	Flexibility of material handling system	☐	☐	☐	☐	☐
H	Similarities of parts in the system	☐	☐	☐	☐	☐

	Factors affecting Product Flexibility	**Very Low** **1**	**Low** **2**	**Moderate** **3**	**High** **4**	**Very High** **5**
A	Design changes required in the product	☐	☐	☐	☐	☐
B	Variety of products	☐	☐	☐	☐	☐
C	Offline part programming preparation facility	☐	☐	☐	☐	☐
D	Number of existing part families matching the new product design	☐	☐	☐	☐	☐
E	Machine flexibility	☐	☐	☐	☐	☐

9. Please indicate the level of following factors affecting in the design and implementation of Automated Guided Vehicle (AGV) in your company**:**

Factors affecting design and implementation of AGVs		**Very Low 1**	**Low 2**	**Moderate 3**	**High 4**	**Very High 5**
A	Number of AGV's required	☐	☐	☐	☐	☐
B	Volume of production	☐	☐	☐	☐	☐
C	Traffic management technique	☐	☐	☐	☐	☐
D	Layouts of AGV tracks in the industry	☐	☐	☐	☐	☐
E	Economical problem	☐	☐	☐	☐	☐
F	Difficulty in changing organization culture	☐	☐	☐	☐	☐
G	Level of preventative maintenance	☐	☐	☐	☐	☐
H	Poor information system	☐	☐	☐	☐	☐
I	Poor selection of process sequence	☐	☐	☐	☐	☐
J	Long period of implementation	☐	☐	☐	☐	☐
K	AGV's path layout	☐	☐	☐	☐	☐
L	Positioning of idle vehicles	☐	☐	☐	☐	☐
M	Battery management	☐	☐	☐	☐	☐
N	Failure management	☐	☐	☐	☐	☐
O	Decision regarding provision of control zone	☐	☐	☐	☐	☐
P	Queue capacity of each machine	☐	☐	☐	☐	☐

Q	Investment according to current & future manufacturing requirement	☐	☐	☐	☐	☐
R	Shortest path route	☐	☐	☐	☐	☐
S	Poor communication	☐	☐	☐	☐	☐
T	Lack of standard procedure	☐	☐	☐	☐	☐
U	Capacity of buffer for the vehicle	☐	☐	☐	☐	☐
V	Proper training	☐	☐	☐	☐	☐
W	Speed of AGV’s	☐	☐	☐	☐	☐

10. Please assign the weight to the following indicators in measuring the performance of flexible manufacturing system**:**

	Measures related to Finance	**Very Low 1**	**Low 2**	**Moderate 3**	**High 4**	**Very High 5**
A	High profit margins	☐	☐	☐	☐	☐
B	Return on investment (ROI)	☐	☐	☐	☐	☐
C	Growth in market share	☐	☐	☐	☐	☐
D	Value-aided production	☐	☐	☐	☐	☐
E	Reduction of warranty costs	☐	☐	☐	☐	☐
F	Costs of sold goods	☐	☐	☐	☐	☐

	Measures related to Customers	**Very Low** **1**	**Low** **2**	**Moderate** **3**	**High** **4**	**Very High** **5**
A	Improved product quality	☐	☐	☐	☐	☐
B	Timely delivery	☐	☐	☐	☐	☐
C	Improved flexibility	☐	☐	☐	☐	☐
D	Perfect order fulfillment	☐	☐	☐	☐	☐
E	Customer satisfaction	☐	☐	☐	☐	☐
F	Cost of product	☐	☐	☐	☐	☐
G	Maintenance cost	☐	☐	☐	☐	☐
H	Life of product	☐	☐	☐	☐	☐
I	After delivery services	☐	☐	☐	☐	☐

	Measures related to internal Business	**Very Low** **1**	**Low** **2**	**Moderate** **3**	**High** **4**	**Very High** **5**
A	Inventory turnover ratio	☐	☐	☐	☐	☐
B	Assets utilization	☐	☐	☐	☐	☐
C	Throughput time	☐	☐	☐	☐	☐
D	Reduction in WIP & queues	☐	☐	☐	☐	☐
E	Reduced waste	☐	☐	☐	☐	☐
F	Flexible environment	☐	☐	☐	☐	☐
G	Time compression	☐	☐	☐	☐	☐
H	On time delivery	☐	☐	☐	☐	☐
I	Better integration	☐	☐	☐	☐	☐

	Measures related to innovation and knowledge	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
A	Flexible production	☐	☐	☐	☐	☐
B	Process innovation	☐	☐	☐	☐	☐
C	Product innovation	☐	☐	☐	☐	☐
D	Awareness of challenges ahead	☐	☐	☐	☐	☐
E	Accurate data and information system	☐	☐	☐	☐	☐
F	Dynamic and proficient manager	☐	☐	☐	☐	☐

	Operational measures	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
A	Makespan	☐	☐	☐	☐	☐
B	Flow time per item	☐	☐	☐	☐	☐
C	Delay time at local buffers	☐	☐	☐	☐	☐
D	Machine utilization	☐	☐	☐	☐	☐
E	Processing time	☐	☐	☐	☐	☐
F	Shifts overtime	☐	☐	☐	☐	☐
G	Setup time	☐	☐	☐	☐	☐
H	Routing flexibility	☐	☐	☐	☐	☐
I	Number of parts produced	☐	☐	☐	☐	☐
J	Lead time	☐	☐	☐	☐	☐
K	Good performance measuring techniques	☐	☐	☐	☐	☐

L	Skilled workers	☐	☐	☐	☐	☐
M	Multi-functional machines	☐	☐	☐	☐	☐
N	Type and number of operations	☐	☐	☐	☐	☐

11. Please indicate the level of following factors affecting in the design and development of flexible fixture and pallets**:**

	Factors affecting flexible fixture and pallets	**Very Low 1**	**Low 2**	**Moderate 3**	**High 4**	**Very High 5**
A	Level of WIP allowed	☐	☐	☐	☐	☐
B	Flexibility of fixtures	☐	☐	☐	☐	☐
C	Clamping force required in the fixture	☐	☐	☐	☐	☐
D	Cost effectiveness of fixture	☐	☐	☐	☐	☐
E	Fixture setup time	☐	☐	☐	☐	☐
F	Workpiece deformation	☐	☐	☐	☐	☐
G	Capacity of pallet	☐	☐	☐	☐	☐
H	Swing diameter	☐	☐	☐	☐	☐
I	Easy loading & unloading of parts from fixture	☐	☐	☐	☐	☐
J	Safety	☐	☐	☐	☐	☐
K	Difference in the part style and size	☐	☐	☐	☐	☐
L	Ease with which parts can be loaded or unloaded from the fixture	☐	☐	☐	☐	☐

Respondent Profile

1. Name (If you please): ……………………………………………………

2. Designation:

(a) CEO [ ] (b) Sr. Manager [ ] (c) Manager [ ] (d) Dept. Manager [ ]

(e) Engineer [ ] (f) Junior Staff [ ]

3. Your association in years with current organization:

(a) Less than 5 [ ] (b) 5-7 [ ] (c) 8-10 [ ] (d) More than 10 [ ]

APPENDIX A2

BRIEF PROFILE OF THE RESEARCH SCHOLAR

Suman Gothwal is working as an Assistant Professor in the Department of Mechanical Engineering, Northern India Engineering College (NIEC), New Delhi, India. She has also worked as an Assistant Professor in the Department of Mechanical Engineering, Faculty of Engineering and Technology (FET), Manav Rachna International University (MRIU), Faridabad, India. She passed her B.E. Mechanical from Netaji Subhas Institute of Technology (NSIT), Delhi in Manufacturing Process and Automation Engineering (MPAE), M.Tech in Manufacturing Technology and Automation from the YMCA University of Science and Technology, Faridabad, India and pursuing her Ph.D research from the same University (YMCA). Her area of interests is manufacturing technology and automation. Her research papers are published/accepted in Internatonal Journal of Services and Operations Management, International Journal of Manufacturing Technology and Management and International Journal of System Assurance Engineering and Management, International Journal of Process Management and Benchmarking.

APPENDIX A3

LIST OF PUBLICATIONS OUT OF THESIS

List of published Papers in International Journals

Sr. No.	Title of Paper	Name of Journal	Vol. and Issue No.	Year of Publication	Page No.
1	Different aspects in design and development of flexible fixtures: review and future directions	International Journal of Services and Operations Management (Inderscience)	Vol. 26, No. 3	2017	386-410
2	Analyzing the factors affecting the flexibility in FMS using Weighted Interpretive Structural Modeling (WISM) approach	International Journal of System Assurance Engineering and Management (Springer)	Vol. 7, No. 2	2016	1-15
3	Performance evaluation of flexible manufacturing system using diagraph and matrix/GTA approach	International Journal of Manufacturing Technology and Management (Inderscience)	Vol. 30, No. 3/4	2016	253-276

Lists of Accepted Papers in International Journals

Sr. No.	Title of Paper	Name of Journal	Present Status	Vol. and Issue No.	Year of Publication
1	Conceptual Design and Development of pneumatically controlled flexible fixture and pallets	International Journal of Services and Operations Management (Inderscience)	In production	Not Assigned	2017
2	Optimization of AGV's path layout in flexible manufacturing System (FMS) using 0-1 Linear Integer Programming	International Journal of Process Management and Benchmarking (Inderscience)	In production	Not Assigned	2017
3	Prioritizing the performance measures of FMS using multi-criteria decision making (MCDM) approaches	International Journal of Process Management and Benchmarking (Inderscience)	In production	Not Assigned	2017
4	A comparative study of multi-criteria decision making approaches for prioritizing the manufacturing systems	International Journal of Process Management and Benchmarking (Inderscience)	In production	Not Assigned	2017