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Selection of lean manufacturing systems using the analytic network process – a case study

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Abstract

Purpose – Lean manufacturing (LM) has attracted the attention of industries all over the world. Many operation managers have implemented or will be implementing LM because of the benefits reported by other companies or because their customers have demanded it. This paper aims to present a case study of a medium-sized valve manufacturer in which the decision of implementing LM is made by analyzing the capabilities, practices, tools and techniques of alternative manufacturing systems apart from understanding its effect on the decision areas of the operations department.

Design/methodology/approach – A multi attribute decision making (MADM) model, namely, the analytic network process (ANP) has been used for this purpose, which structures the problem related to selection of alternative manufacturing systems in a hierarchical network form. In this problem, it links the performance measures or competitive priorities, decision areas, and the elements with alternatives available to the decision maker and provides a holistic framework for the selection of alternative manufacturing systems to achieve the competitive priorities of the organisation under study.

Findings – From an extensive analysis of the results, under the given circumstances, it is evident that implementation of a lean manufacturing system (LMS) is a better alternative, as it would result in overall improvement in the performance of an organisation in comparison with the alternatives.

Practical implications – This paper demonstrated a step-by-step approach of the ANP model using a case study of a small- and medium-sized enterprise, which makes it more suitable for managers to learn and adopt such MADM models to support their decisions.

Originality/value – To the author's knowledge, there is no paper available in the existing literature that discusses the application of ANP in the field of LM.

Keywords Decision making, Systems analysis, Small to medium-sized enterprises, Lean production

Paper type Research paper

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1. Introduction

The effect of globalisation and opening up of world markets created turbulence in the business environment thereby pressurizing the executives and managers of organisations to make everything faster. Many organisations worldwide are in the race to attain this invincible status of being a world-class manufacturer (WCM) by transforming their manufacturing systems based on the principles and philosophies proposed by experts from Japan or Western world. For example, Mukhopadhyay and Shanker (2005) discussed the implementation of the just-in-time (JIT) principles such as kanban systems, setup time reduction, housekeeping practices, etc. in a continuous product line of a tyre manufacturing plant in India. Savolainen (2000) suggested two successful leadership strategies for gaining business excellence through total quality management (TQM). They provided a couple of Finnish case examples to reinforce that inimitable competitive advantage can be gained through a deeply embedded quality ideology. In another study, Tsang and Chan (2000) presented a case study of TPM implementation in a factory, which had the vision of being one of the top three semiconductor equipment suppliers in the world. On the other hand, some of the industries followed the Western philosophies such as lean manufacturing (LM), agile manufacturing, six sigma (SS) to achieve a better competitive advantage. For instance, Seth and Gupta (2005) discussed about application of value stream mapping (VSM) for productivity improvement of an Indian company and reported about the gain in production output per person and reduction of work in process and finished goods inventory. Ehie and Sheu (2005) investigated the potential of combining SS and theory of constraints (TOC) and proposed an integrated TOC/SS framework, which was applied in an axle manufacturing company to improve its gear-cutting operation. They found that the company benefited tremendously from its emphasis on global improvement guided by the TOC concept.

In addition to the above cases, there are some managers, who believe that they can achieve superior competitive advantages through the implementation of sophisticated computer integrated technologies such as automation, flexible manufacturing systems (FMS) or computer integrated manufacturing systems (CIMS). Narain *et al.* (2004) presented the findings of case studies carried out in two large Indian manufacturing organisations (involved in making shoes and railway coaches) to highlight the status of adoption of FMS. They explained that the move to implement FMS was triggered by the external stimuli of customers and competitors for the first firm (shoe manufacturer), while it was the sheer varieties of products, which forced the second firm (railway coach manufacturer) to adopt FMS. Coffey and Thornley (2006) emphasised that the future for auto industries lies in utilising automation along with the principles of LM. These cases substantiated that the managers would have believed that implementing such management-based philosophies or technology-based systems can catapult the organisations to achieve the goals of WCM. But in all these cases, the following question still remain unanswered – "How the managers or executives would have made a decision of implementing such advanced manufacturing management philosophies or technically sophisticated systems in their organisations?" In most of the industries, managers tend to make such decisions because of the benefits reported by other companies across the world or because their customers have demanded it as explained by Narain *et al.* (2004). Wu (2003) too stated that "customers can obtain improvements in quality and delivery by motivating suppliers to adopt JIT production and JIT delivery". Thus, it is believed that only a very few managers would have made a decision of implementing such advanced manufacturing management philosophies or technically sophisticated systems in their organisations, based on their own assessment. Hence, in this paper, an attempt has been made to:

- describe a case study of a small- and medium-sized enterprise (SME), which is losing its competitive position due to the problems faced;
- explain how the managers or representatives of the case organisation made a decision of adopting either a manufacturing philosophy like lean manufacturing systems (LMS) or a technically sophisticated CIMS to resolve their problems, by analyzing the capabilities, practices, tools and techniques of alternative manufacturing systems and relating the same with respect to their competitive priorities;
- discuss the application of a MADM model, namely, the analytic network process (ANP) for the selection of manufacturing systems; and
- demonstrate how the representatives of the case organisation utilised ANP and selected LMS as a manufacturing philosophy to transform their manufacturing systems.

The paper is arranged as follows: Section 2, provides an overview about the case organisation while Section 3, describes the literature review about the alternative manufacturing systems CIMS and LMS that are considered by the case organisation. Section 4 gives an introduction to MADM models and in particular about ANP, its application and its suitability for the problem under study. Section 5, describes the algorithm of ANP and explains in detail how it was utilised for the selection of a manufacturing system by the case organisation. Section 6 deals with the results and discussion, while Section 7 ends with conclusions.

2. An overview about the case organisation

The organisation considered for case study is a medium-sized valve manufacturer located in the north-western part of India. It manufactures different types of valves (relief valves, flow control valves, etc.) and its associated components. These valves are predominantly used in pressure vessels. The case organisation is one of the first tier suppliers to the pressure vessel manufacturers. Table I presents a summary about the case organisation.

Table I.
A summary about the case organisation

Industry characteristics	Details about the case organisation
Industry type	Discrete type manufacturing
Industry sector	Power sector
Product	Different types of valves and its associated components
Product type	Critical components
Production volume and variety	Medium volume and medium variety
Company vision	To be a star performer and market leader
Mission	Continuous improvement of products, processes and people

The organisation is currently facing many problems in terms of not being able to meet its competitive priorities. Following are some of the problems that are faced by the organisation:

- *High variety and low volume.* The design of valves is highly varying because it is customised for the type of pressure vessels built. This resulted in a variety of valves under each type and naturally, the number of associated components and spares is also very high. On the other hand, the volume for each type of valves is low, which naturally increased the number of stock keeping units for the organisation. In addition to this problem, most of the valves and its associated parts differ in terms of dimensions, design (shape) and materials used, which makes the organisation to carry out a lot of setup and material handling activities.
- *Quality concerns.* Valve is considered to be one of the critical components in the pressure vessel assembly as it is concerned with the safety of the product as well as that of user. Hence, the valve and its associated components have to be precisely machined and there is no room for even a slight deviation from the specifications. In the past, the company had faced few quality problems and some of their lots were returned even for a slight deviation from the specifications resulting in significant losses to the tune of around Rs 12 lakhs.
- *Delivery.* Since the requirement of power is growing in India, the market for pressure vessels is also increasing. Naturally, the demand for the valves and its associated components are increasing and it is expected to rise further in the future too. Hence, on one hand, the company was expecting more orders from the customers, but on the other hand, the orders were not appreciably increasing as expected by the company. On analysing the problem, they found that the delivery performance of the company was not well appreciated by their clients. Even though they made efforts to supply a fairly good quality product, they had problems in meeting the deadlines and target. They found that their on-time delivery record was just 75 per cent.
- *High cost.* Adding fuel to their existing internal problems, the number of competitors in the valve market has started to increase resulting in increased cost pressure for the organisation. Further, in the last two years, the material cost, labour cost and energy costs were also spiralling upwards, but the clients of the case organisation were emphasising on continuous price reduction every year as per their long-term contract.

The manufacturing of valves and other components is currently done with the help of semi-automatic, general purpose machines and few fully automatic turning and machining centres. They follow a job shop type of production as they need to produce different types and sizes of valves as per the requirement of their varied client base. The number of people on roll at present is around 80. Though, the case organisation is poised for growth and would like to increase its market share, the management is worried about the above-mentioned problems. The managers in the top level would like to make changes and transform their existing manufacturing systems and are in the process of laying out strategies and policies to become a WCM of valves in India within the next five years. They were contemplating on the following alternatives to resolve the above-mentioned problems:

- a highly sophisticated and technically intensive CIMS; and
- a highly practical and management oriented LMS.

Though it is a medium-sized enterprise, the managers have identified CIMS as one of the alternatives based on the existing technology they possess and from the perspective of economy of scale, assuming an increase in demand in the future. The organisation is currently using the following computerised systems:

- *Computer aided design (CAD).* They use software packages like AutoCAD for the purpose of designing the tools, fixtures and other material handling systems apart from generating the drawings and documents of their products.
- *Computer aided manufacturing (CAM).* They also use computerised numerical control (CNC) machines as they possess couple of turning and machines centres apart from semi-automatic machines. In addition to this, they have also incorporated local automation for some machines as part of their productivity improvement activities carried out earlier.
- *Computer aided production planning and control.* They perform the production planning and scheduling activities using standalone planning software developed indigenously, which uses spread sheet applications like excel and access as backend database.

On the other hand, the top management was also open to implement management philosophies such as LMS. This is because, as a first tier supplier to pressure vessel manufacturers, they have obtained the ISO 9000 certification, which have shown them good results in the past as they could standardise various processes apart from reducing defects. Hence, they were contemplating on implementing such manufacturing management practices and philosophies. But the issue here is how to choose between the LMS and CIMS? The decision cannot be based on just one factor – for instance, the cost involved for these two alternatives. A proper decision requires analysis from multiple perspectives. Hence, the authors were called upon to supplement their decision-making effort. To enlighten the top level managers of the case organisation about the alternatives, a detailed literature review was carried out by the authors to understand about the alternate manufacturing systems based on their capabilities, benefits, tools and techniques used, etc.

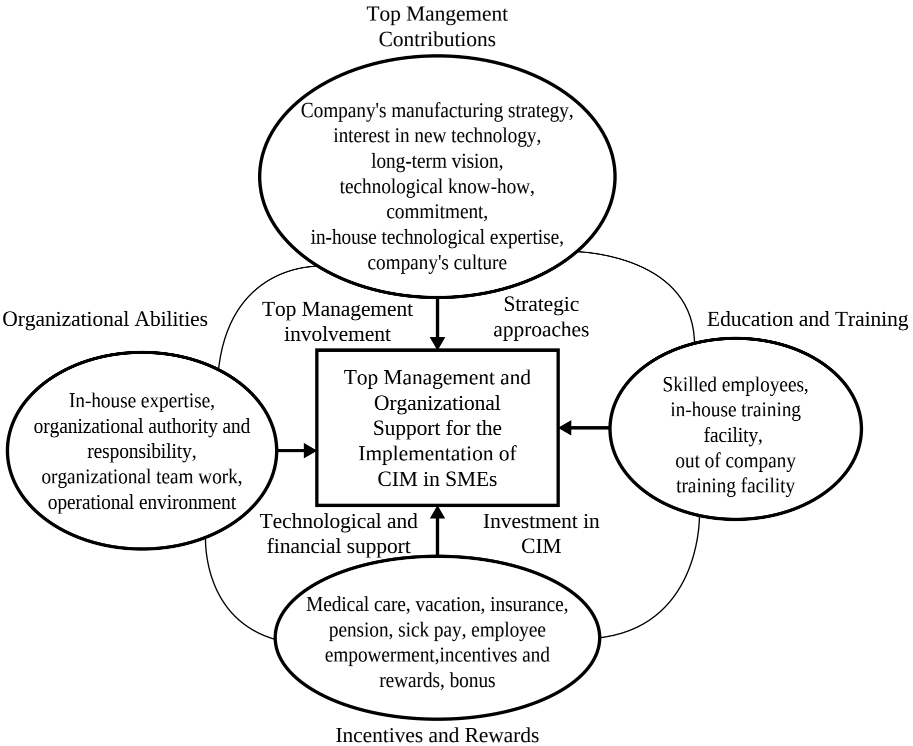
3. Literature review

3.1 Computer integrated manufacturing systems

According to Groover (2001), CIMS denotes the pervasive use of computer systems to design the products, plan the production, control the operations, and perform various business related functions needed in a manufacturing firm. Attaran (1997) presented different case studies, in which US firms like Motorola, Allen Bradley, Texas Instruments and Tandem Computers have successfully applied CIM and capitalized on the advantages of such advanced technology. He explained about the barriers to factory automation and the steps for successful implementation apart from examining technologies that enhance CIM implementation. On the other hand, Caputo *et al.* (1998) developed a methodology for introducing CIM technology in small companies and identified the actual situation or factors which favour small companies in developing and implementing CIM applications. They have also claimed that the introduction of CIM technologies may be one of the most promising strategies to acquire and maintain a competitive edge, particularly for small companies. Similarly, Gunasekaran *et al.* (2000) also reviewed the literature on the design and implementation of CIM and have developed a generalized practical framework for the design and implementation of CIM in SMEs. In another study, Gunasekaran and Thevarajah (1999) analyzed empirically the implications of CIM in British SMEs using a questionnaire that was adapted from Nakamura's model to suit their study. They analyzed the economic impact (which includes the combined influence of profitability, operating risk and present net value), strategic impact (which includes the characteristics of a company, in terms of customer satisfaction, reduction in lead time, improved quality of products and improved market share), the social impact (concerning the changes in the nature and level of labour loading, union relations, labour productivity, training requirements, and motivation), the operational impact (which includes aspects such as delivery schedule performance, productivity, inventory, maintainability, flexibility and quality control). Marri *et al.* (1998) referred the definition of Lefebvre *et al.* and discussed about the components of CIMS as follows: CIM is concerned with providing computer assistance, control and high-level integrated automation at all levels in manufacturing (and other) industries, by linking islands of automation into a distributed processing system. These isolated automated production islands include NC machines, distributed numerical control (DNC), computerised numerical control (CNC), material requirement planning (MRP), manufacturing resource planning (MRP II), CAD, computer-aided process planning (CAPP), computer-aided manufacturing (CAM), automated storage, computer controlled material handling equipment, and robotics. Similarly, Gunasekaran *et al.* (2001) analysed the implications of organisation and human behaviour due to implementation of CIM in SMEs and explained that it requires cross-functional co-operation, and involvement of employees in product and process development. Apart from this, they highlighted that a successful CIM initiative in SMEs must have top management involvement and commitment and a CIM compatible organisational infrastructure which includes requisite skills, appropriate training and education, and adequate incentives and rewards. Hence, to promote a better understanding of such organisational issues pertaining to the implementation of CIM in SMEs, they proposed a framework based on literature review and empirical study for examining and explaining the organisational ramifications of CIM. Figure 1 shows a model for illustrating the role of organisational and human behaviour in the implementation of CIM in SMEs.

3.2 Lean manufacturing systems

The researchers Womack *et al.* (1990) from Massachusetts Institute of Technology, USA have coined the word "Lean Production (LP)" after their landmark study titled "International Motor Vehicle Program (IMVP)", which investigated productivity and management practices in the motor industry involving 52 vehicle assembly plants in 14 different countries around the world. The proponents argued that LMS have universal applicability. But some researchers like Cooney (2002) questioned the universality of lean and emphasized that it cannot transform the traditional manufacturing systems (TMS) like craft and mass production systems rather these



Source: Gunasekaran *et al*. (2001)

Figure 1.
A model for illustrating the role of organizational and human behaviour in the implementation of CIM in SMEs

production systems can adopt LP practices. This is indeed true; however, LM can really transform them. There are adequate evidences available in the literature in the form of case studies, which support the claim that the LM practices have a universal appeal. For example, Parry and Turner (2006) described three case studies about Rolls Royce, Airbus and Weston Aerospace in UK that has been practicing LM. Dhandapani *et al.* (2004) presented a case study of a steel company that applied some aspects of lean thinking and have explained that per annum production costs can be reduced by 8 per cent of turnover, while capital equivalent to 3.5 per cent of turnover can be released through the removal of inventory. Lee and Allwood (2003) investigated how LM can be applied to temperate dependent processes with interruptions. Thus, these cases substantiate that LM has been implemented in project shops (aerospace industries), in a continuous production industry (steel mills) and also in a batch production environment (forging) apart from mass production industries. Similarly, Karlsson andÅhlström (1997) developed a framework to represent the theoretical concept of the lean enterprise and studied how it can be applied in a SME. Detty and Yingling (2000) developed a simulation model and quantified the benefits of the LM. Chang and Lee (1996) identified the specific factors needed for the successful implementation of JIT techniques, which includes: top management support; bottom-up management style; participation of all employees; education and training; good relationship with vendors; good relationship with customers; communication between production department and marketing department; union support; total quality control; quality circles (QC), statistical process control (SPC) and integration of MRP or MRP II and JIT.

LMS consists of different principles, tools, techniques, procedures and practices (from now on, they will be referred as elements/attributes and sub-elements or sub-attributes). Feld (2001) noted that LM consists of five primary elements: manufacturing flow, organisation, process control, metrics/performance measures and logistics. Under these elements, he categorized various tools, techniques and practices of LM as sub-elements. Similarly, many authors have identified the elements and sub-elements of LM. Treville and Antonakis (2006) explained that the demanding factory physics of LP are achieved over time through a combination of synergistic and mutually reinforcing practices, which can be grouped into several complementary subsystems including (but not limited to) JIT manufacturing, TQM, TPM, Kaizen (continuous improvement), design for manufacturing and assembly, supplier management and human resources management (HRM) practices under the "respect-for-workers" umbrella serving as the glue to hold the overall system together. Shah and Ward (2003) listed out 21 elements based on the literature review and categorized them into four practice bundles associated with JIT, TPM, TQM and HRM. But, it is our opinion that when LM is considered as a manufacturing system, the elements identified earlier by other researchers were not comprehensive. For example, in the study of Shah and Ward (2003), important elements such as "mixed model manufacturing", "one piece flow", "Andon or Jidoka", etc. were missing. Hence, we undertook a meta-analysis of the literature in another study to identify a comprehensive list of most commonly used LM elements (Anand and Kodali, 2007). From this analysis (which is not shown in this paper), a consolidated list of around 60 LM elements, were identified. Table II shows the consolidated list of LM elements.

3.3 Choosing the manufacturing system

The definitions regarding manufacturing, a system and manufacturing systems have been well established. Any standard text book on "Operations Management" would provide these definitions and a description about the decision areas or functions of operations department in an organisation. For example, Russell and Taylor III (2006) identified the different functions or activities (decision areas) carried out by an operations department, which include: operations strategy, product design, process planning (PRP), facilities and layout, purchasing, production planning and control, quality control, maintenance, human resources, logistics and supply chain management, etc. Figure 2 shows the typical functions or activities (decision areas) carried out by an operations department.

Implementing any of the alternative manufacturing systems considered above will affect the operations department of the case organisation and the decision areas associated with it. Hence, the authors felt that the evaluation of alternative manufacturing systems can be carried out from this perspective. Some of the decision areas like capacity, information support systems, etc. are not considered for analysis separately, as the decisions or activities related to it are already considered in other decision areas. For example, decisions like use of software packages related to CAD/CAM or enterprise resource planning (ERP) fall under the decision area of information systems. But in this paper, these decisions were considered to be a part of product design and production planning and control activities of operations

S. no.	Element	In short
	Product design	*PRD*
1	Design simplification	DSN
2	Use of standardized parts	USP
3	Modular design	MDN
4	Concurrent engineering	CEG
5	Design for manufacturing	DFM
6	Supplier involvement in design	SID
7	Platform based design	PBD
8	CAD/CAM	CAD
9	Use of common parts	UCP
	Process planning	*PRP*
10	Cellular manufacturing or group technology	CEM
11	New process or equipment	NPE
12	Use of multiple small machines	UMS
	Facilities and layout	*FAL*
13	Workload balancing	WLB
14	U-shaped cell	USC
15	One piece flow	OPF
16	Standardization of work processes	SWP
	Purchasing	*PUR*
17	Sole sourcing	SOS
18	Frequent multiple small lot delivery	FMD
19	Supplier training and development	STD
20	Long term supplier relationship	LSR
21	Information sharing with suppliers	ISS
	Production planning and control	*PPC*
22	Small lot production	SLP
23	Use of MRP/ERP	ERP
24	Use of EDI with suppliers	EDI
25	Kanban system	KAN
26	Pull production	PUL
27	Mixed model manufacturing	MMM
28	Production smoothing	PRS
	Manufacturing	*MAN*
29	Automation	AUN
30	Visual control	VIC
31	Single minute exchange of dies	SMD
32	Andon and Jidoka	ANJ
33	Standard containers	STC
34	Maintain spare capacity	MSC
35	Focused factory production	FFP
	Continuous improvement	*COI*
36	Housekeeping or 5S	HOK
37	Use of problem solving tools	PST
38	Work-in-process inventory reduction	WIP
39	Value stream mapping	VSM
40	Reduction of safety stock	RSS
41	Cycle time and lead time reduction	CTR
	Quality control	*QCO*
42	Statistical process control	SPC
43	Defects at source through successive check	DES

(*continued*)

Table II.
Consolidated list of LM elements

S. no.	Element	In short
44	Pokayoke or defect prevention	POK
45	Customer feedback	CUF
46	Quality circles	QUC
	Maintenance	*MAI*
47	Autonomous maintenance	AUM
48	Preventive maintenance	PRM
49	Maintenance prevention	MAP
50	Safety improvement	SAI
	Human resource management	*HRM*
51	Multi skilled workforce	MSW
52	Employee empowerment and participation	EEP
53	Flat organisation structure	FOS
54	Rewards and recognition	RER
55	Cross functional team working	CFT
56	Suggestion schemes	SUS
57	Job enlargement or Nagara system	JOE
58	Communication between employees	COE
59	Multi functional training	MFT
60	Job rotation or flexible job responsibilities	JOR

Table II.

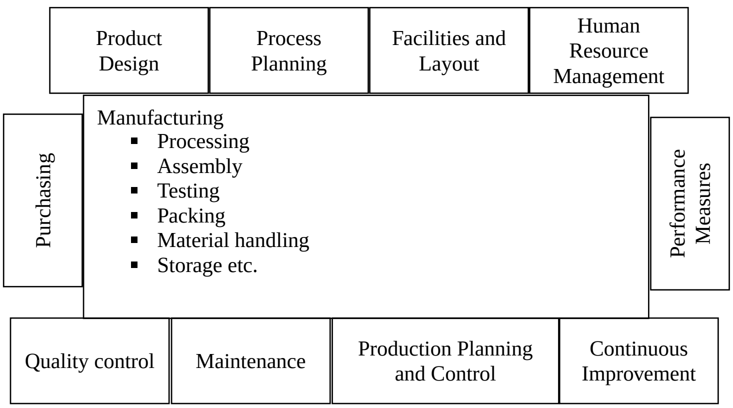


Figure 2.
Typical functions or activities (decision areas) carried out by an operations department

department, which require the use of CAD/CAM/CAE and ERP, respectively. The same argument was presented before the decision-making team of the organisation (which included the president, operations manager and head of industrial engineering department). After an elaborate discussion, a consensus was reached among the team members to make a decision based on how each of these alternative systems will affect the existing operation functions and the associated decision areas. Hence, the elements identified from the comparative analysis was classified according to the functions or activities carried out by an operations department as shown in Table II.

It should be noted that a separate set of elements for CIMS was not identified as it was felt that most of the components of CIMS were also present in the LMS or TMS. Some of the elements of CIMS were already put into use (in the TMS) by the case organisation.

For example, use of CAD, CAM, automation, etc. were already present in the existing system and they were also part of the LMS. Similarly, the organisational and human related aspects for implementing CIMS and LMS are also the same as explained by Chang and Lee (1996) and Gunasekaran *et al.* (2001). Since, there are many elements and sub-elements to be considered and analyzed during decision making, the use of MADM models was suggested by the authors to the decision makers.

4. Analytic network process and its application for the problem under study

There are numerous MADM models available in the literature such as elimination and choice translating reality, Technique for Order Preference by Similarity to Ideal Solution, joint probability decision-making, equivalent cost analysis, multi-attribute utility theory, analytic hierarchy process (AHP), etc. Amongst these models, the most commonly used model is AHP, which was developed by Saaty (1980). Even for the current problem, AHP can be applied. But, it was not utilised because of its inherent limitations.

4.1 Limitations of AHP

According to Shee *et al.* (2003), "most of these traditional MADM methods are based on the additive concept along with the independence assumption, but each individual criterion is not always completely independent". Even AHP has some inherent limitations due to its hierarchical representation. Sarkis and Talluri (2002) have listed the following limitations of AHP:

- Each element in the hierarchy is supposed to be independent, and a relative ratio scale of measurement is derived from pair-wise comparisons of the elements in a level of the hierarchy with respect to an element of the preceding level. However, in many cases, there is interdependence among criteria and alternatives.
- AHP employs a unidirectional hierarchical relationship among decision levels, which implies no influence of lower levels on the upper levels. But it may be possible for the components of the two levels to influence each other (feedback). These relationships cannot be evaluated using AHP.

To overcome these problems, ANP has been suggested for use in solving the decision problem of the case organisation.

4.2 Introduction to ANP

ANP developed by Saaty (1996) is a MADM model which allows for the consideration of the interdependencies among and between different levels of attributes and alternatives. It is a more general form of the AHP approach, incorporating feedback and interdependent relationships among decision attributes and alternatives. It is used for modelling more complex decision environments. ANP does involve representing relationships hierarchically but does not require a strict hierarchical structure as does AHP. According to Meade and Sarkis (1999), it is also called as "models with feedback". Table III shows the differences between AHP and ANP.

AHP	ANP
It is conceptually easy to use; it is decisionally robust so that it can handle the complexities of real world problems (Saaty, 1980)	The ANP is built on the AHP and it is a more generalized approach for modelling more complex decision environments (Saaty, 1996)
AHP models a decision-making framework that assumes a unidirectional hierarchical relationship among decision levels. The top element of the hierarchy (apex) is the overall goal for the decision model. The hierarchy decomposes from the general to a more specific attribute until a level of manageable decision criteria is met	ANP does involve representing relationships, but a looser network structure makes possible the representation of any decision problem without concern for what comes first and what comes next as in a hierarchy (Saaty, 1999)
A hierarchy is linear, with a goal in the top level, and the alternatives in the bottom level	The ANP is a nonlinear structure that deals with sources, cycles, and sinks
AHP assumes that the main elements and sub-elements within main elements are independent of each other	By allowing for dependence, the ANP goes beyond the AHP by accounting for independence among the elements and sub-elements. The ANP deals with dependence within a set of elements (inner dependence), and among different sets of elements (outer dependence) (Saaty, 1999)
AHP assumes that the system's elements are not correlated and are uni-directionally influenced by a hierarchical relation	ANP approach eliminates these limitations and allows a feedback relationship among the criteria at different levels and interdependence between the criteria at the same level through the development of a "Super matrix" (Saaty, 1996)
In the AHP approach there are one-way hierarchical arrows that show a dominance or control of one level of attributes over another set of sub-components or attributes	In the ANP approach, with the allowance of interdependencies occurring among attributes and attribute levels, the graphical representation may include two way arrows (or arcs) among levels. A looped arc is used to show the interdependency relationships that occur within the same level of analysis. The directions of the arcs signify dependence, arcs emanate from an attribute to other attributes that may influence it.

Table III.
Differences between AHP and ANP

4.3 Brief review on applications of ANP

ANP finds applications in various fields. It has been used by numerous authors for solving different types of problems. Meade and Sarkis (1999) used ANP as the decision-making methodology for the evaluation of alternatives (e.g. projects) to help organisations become more agile, with a specific objective of improving the manufacturing-business processes. In order to evaluate alternatives that impact the business processes, a networked hierarchical analysis model based on the various characteristics of agility, is proposed. Similarly, Cheng and Li (2004) applied ANP for contractor selection while Agarwal *et al.* (2006) used ANP-based approach for modelling the metrics of lean, agile and leagile supply chain. They explored the relationship among lead-time, cost, quality, and service level and the leanness and agility of a case supply chain in fast moving consumer goods business and concluded with the justification of the framework, which analysed the effect of market winning criteria and market qualifying criteria on the three types of supply chains (lean, agile and leagile). In the above described cases, the authors have used ANP as a standalone decision-making tool. On the other hand, some researchers have used ANP in conjunction with another tool or technique. For example, Karsak *et al.* (2002) combined goal programming approach with ANP for product planning in quality function deployment (QFD). Apart from this, the literature related to ANP is inundated with diverse applications in fields such as location of a hub (Sarkis and Sundarraj, 2002), R&D project selection (Meade and Presley, 2002), measuring long-term performance of an organisation (Yurdakul, 2003), vendor selection (Bayazit, 2006), etc. One of the reasons for using ANP for variety of applications can be due to the fact that it is capable of solving problems when complex interrelationships between the attributes are involved. But till now, to the author's knowledge, there is no application of ANP in the field of LM and in particular it is not being used to make a decision of selecting a manufacturing system. This paper presents the application of ANP in a SME, in which they have made use of this technique to select a suitable manufacturing system from the available alternatives to improve their competitive position.

4.4 Application of ANP for the case problem

To select an alternative manufacturing system as a means to improve and maintain the competitive advantage requires proper justification. One school of thought concerning justification of advanced manufacturing systems states that if manufacturing is to be considered as a competitive tool, justification has to become more of a policy decision rather than an accounting or financial procedure, while another school of thought states that advanced manufacturing systems can be "sold" to top-level management only if all relevant costs and benefits are quantified and presented in an easy-to-understand format (Kodali and Sangwan, 2004). For example, Boaden and Dale (1990) have expressed that the justification of the CIM concept should be undertaken in order to demonstrate to an organisation's senior management team that CIM is a worthwhile venture. They also explained that in the case of concept justification, the development of a clear understanding of CIM itself and its implications for the organisation is a vital factor, which supports the former school of thought. On the other hand, Chen *et al.* (1998) have commented that the modelling analysis of the economic view is very important for industrial people to accept the CIM system architecture for their system integration. However, the estimation method for intangible factors would be the main obstacle for its success. Hence, they proposed a modelling formalism combining ABC analysis and AHP method. The problem considered in this case too supports the latter school of thought, which explains that justification has to become more of a policy decision rather than an accounting or financial procedure. We have reviewed extensively about the CIMS and LMS to ensure that the decision makers of the organisation clearly understand about the capabilities, practices, tools and techniques of each manufacturing system. Similarly, the effect of alternative manufacturing systems on the operations department is studied, which refers to understanding of the implications for the organisation. But it must be remembered that very few attempts were made to address the issue of selection or justification based on this premise. The complex, multi-attribute nature of alternative advanced manufacturing systems such as CIMS and LMS may tend to be overwhelming for analysis by decision makers, without the use of multi-attribute decision models like the ANP.

4.5 Participants for the ANP study

As said earlier, for the ANP study, the president of the organisation, operations manager and the head of industrial engineering department participated in addition to the authors, in which one of the authors was assigned the job of recording the weight values during pair-wise comparison. To proceed with ANP, the following activities have to be carried out:

- A thorough understanding of the problem is required: the discussion in Section 3 already revealed the list of issues faced by the organisation and possible counter measures which the organisation is willing to take in the form of establishing alternative manufacturing systems.
- Selection of attributes or elements affecting the problem: the selection of attributes or elements and sub-attributes or sub-elements relevant to the problem has been determined through literature survey and discussions held with experts. A similar approach was also followed by Agarwal *et al.* (2006), Kodali and Chandra (2001), etc. For this problem, the categorisation scheme (decision areas) and the identified lean elements shown in Table II are referred as the attributes and sub-attributes, respectively.

Before starting the ANP study and collecting the weight values, the attributes and sub-attributes were discussed with the team members and a brief explanation was provided to the participants about each of them. Some of the definitions and the classification of attributes and sub-attributes created confusion among the representatives of the organisation, but after a thorough discussion, they got clarified and a consensus was reached. The pair-wise comparison weight values for the study were gathered through real-time meeting and discussions. The participants deliberated about the weight values before agreeing upon the given values. In the next section, a step-by-step approach of the ANP methodology has been presented.

5. ANP methodology

The entire problem of modelling the elements into hierarchical network, entering the pair-wise comparison values and synthesizing the results were carried out using a test version (β) of the "Super Decisions" software created by Creative Decisions Foundation. But utilising the software prevents a user from understanding the step-by-step approach of ANP. Hence, it is necessary to understand the algorithm of ANP in a detailed manner. Saaty (1999) discussed in detail about the steps to be followed in ANP incorporating interdependencies and feedback in decision making. In this section, the algorithm for ANP and its application has been explained in a step-by-step manner as we move along with the case study. It consists of mainly six stages and each stage has different steps associated with it.

5.1 Stage 1: model construction and problem structuring

Step 1. Identification of control criteria, clusters, elements and alternatives: to structure the decision problem and develop the ANP model, the goal, control criteria, clusters, elements and alternatives have to be identified. In our case problem:

(1) The main goal or objective is to select the best manufacturing system which can improve the performance of the case organisation. The alternatives considered are:
   - existing system or TMS;
   - CIMS; and
   - LMS.
(2) The selection of the best manufacturing system is based on the competitive priorities. In ANP terminology, it will be referred as control criteria, which includes:
   - productivity (PRO);
   - quality (QUA);
   - cost (COS);
   - delivery (DEL);
   - Morale (MOR);
   - flexibility (FLE); and
   - innovation (INN).
(3) Similarly, the attributes and sub-attributes identified in Table II will be termed as the clusters and elements, respectively, according to the ANP terminology. The clusters refer to the decision areas, which are affected by the implementation of alternative manufacturing systems, i.e. the entries that are highlighted in Table II represent the cluster name, while the remaining attributes, which are grouped under each decision area, represent the elements.

Step 2. Represent the relationships of control criteria, clusters, elements and alternatives in the form of a model. The model can be structured as a network model as shown in Bayazit (2006) or as a hierarchical network model as shown in Agarwal *et al.* (2006) and Sarkis and Sundarraj (2002), with the main goal at the top and the alternatives at the bottom, similar to the hierarchical structure of AHP. In the hierarchical structure, the influence of a higher level on a lower level is shown by a down arrow (↓), while the interdependencies within a component or within a level is shown with a looped arc. The control criteria, clusters and elements identified for the case problem are represented in the form of a hierarchical network. Figure 3 shows the main hierarchical network representation of the ANP model for the selection of best alternative manufacturing systems.

In the case problem, the goal is to select the best alternative manufacturing system. The selection will be based on the competitive priorities of the organisation which are considered as the "control criteria". In organisations, the top management gives priorities or importance ranking for the control criteria during the strategic-decision process which will affect further decisions taken downstream. In other words, the control criteria have dominance over the different decision areas of the operations department. Each decision area work according to the competitive priorities set forth by the top management. The decision areas may adopt

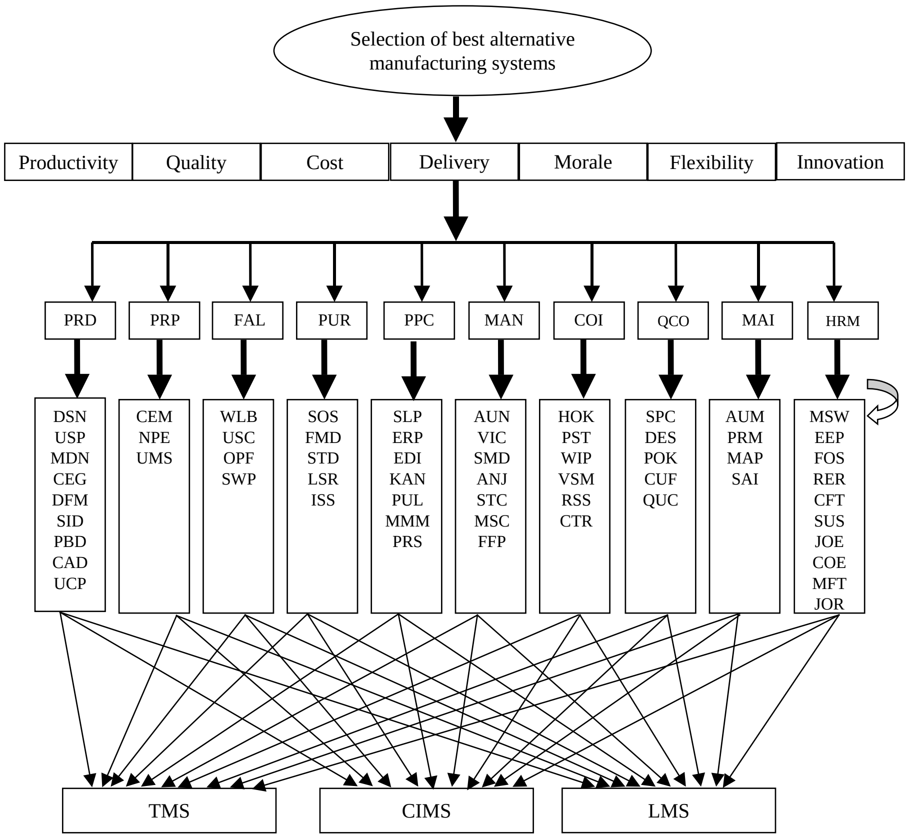


Figure 3. Main hierarchical network representation of the ANP model for the selection of best alternative manufacturing systems

certain practices or procedures or use certain tools, techniques, to achieve the objectives of competitive priorities (control criteria). These tools, techniques, practices procedures, etc. are called as “elements”. The sub-attributes listed in the Table II under each of the decision areas represent the elements. These elements are grouped according to the decision areas it affects. Hence, the decision areas are called as clusters. In addition to this, there exist some interdependencies between the elements within the clusters. Hence, a looped arc is shown in the figure along with a clear dependence relationship between elements. For example, in the facilities and layout cluster, to obtain a “continuous one piece flow”, proper “workload balancing” is required. ANP uniquely captures the interdependencies at different levels of the control hierarchy as well as interdependencies that are inherited among different hierarchies.

Based on the above discussion, it is possible to construct “seven” sub-networks in the ANP model of our problem – one for each control criterion, namely, productivity, quality, cost, delivery, flexibility, morale and innovation. Figure 4 shows a sample sub-network representation of a control criterion – productivity.

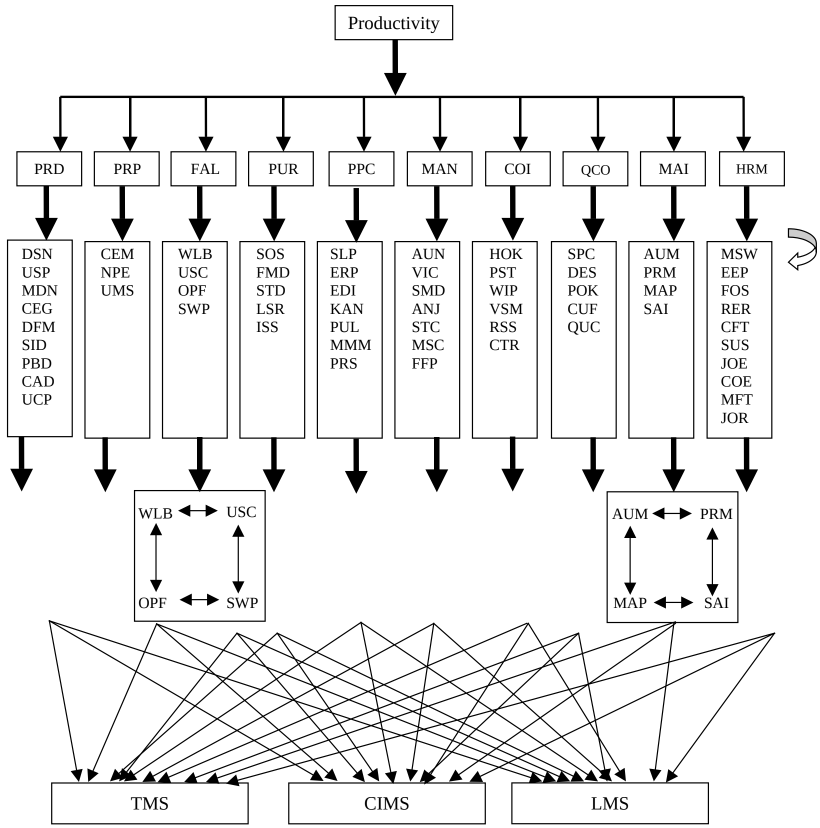


Figure 4.
Sub network representation for the control criterion – "productivity"

5.2 Stage 2: pair-wise comparisons between element and cluster levels

Pair-wise comparisons are carried out between the clusters as well as the elements to find out the importance of a cluster or element over the other cluster or element with respect to the corresponding control criteria. A scale having a range of 1-9, similar to the one used in AHP will be used for comparing where 9 indicates overwhelming dominance and 1 indicates equal importance. This stage consists of the following steps.

5.2.1 Pair-wise comparison at element level.

Step 3. Pair-wise comparison is carried out between the elements with in a cluster with respect to one of the control criterion. A matrix will be formed and the relative weights of each cluster/element is obtained as the eigenvector (eVector) from the matrix, by using the formula:

$$w_i \frac{\sum_{i=1}^{i}\left(\frac{a_{ij}}{\sum_{j=1}^{J} a_{ij}}\right)}{J}, \qquad (1)$$

where, w_i – weight of the cluster/element i; j – index number of columns; and i – index number of rows.

For example, in this problem, a pair-wise comparison was carried between the elements of one of the clusters – PRP with respect to one of the control criteria – productivity (PRO). Table IV shows a sample pair-wise comparison matrix of elements within the cluster PRP with respect to the control criterion PRO (productivity).

For obtaining the relative weights in Table IV, the authors asked different questions to the representatives of the case organisation. A sample question is: "With respect to productivity, within the PRP cluster, what is the relative importance of cellular manufacturing (CEM) with respect to new process and equipment (NPE)?" The answer was 5 on a scale of 1-9 and this is entered in the second row (CEM), third column (NPE) in Table IV.

Step 4. In a similar fashion, pair-wise comparisons were carried out between elements of other clusters, with respect to the same control criterion. At this stage, for a given control criterion, the number of pair-wise comparison matrices will be equal to the number of clusters.

In this case, for the productivity cluster, nine more pair-wise comparison matrices will be formed for the remaining decision areas such as product design, facility and layout, quality control, etc. apart from the one already formed for PRP. These matrices are not shown due to space restrictions. Thus, in total, ten matrices will be formed for the productivity cluster alone.

Step 5. Similar to the above steps (i.e. Steps 3 and 4), pair-wise comparisons are carried out between elements of clusters with respect to the remaining control criteria. At the end of this step, the number of pair-wise comparison matrices formed will be equal to the product of number of control criterion and number of clusters.

For example, pair-wise comparisons are again carried out between the elements of PRP, but with respect to the other control criteria say, quality. There are seven control criteria and under each control criteria 10 pair-wise comparison matrices are formed. Hence, in all, there will be 70 pair-wise comparison matrices formed at the end of this stage. The eVectors obtained from these matrices will be used in stage – 5 as A^D_{kja}, where k represents the elements, i – component and a represents control criteria.

5.2.2 Pair-wise comparison at cluster level.

Step 6. The pair-wise comparison matrix is developed to determine the importance of clusters with respect to each control criterion. Similar to Step 3, using the equation (1), the eVectors are calculated.

	CEM	NPE	UMS	eVector (A^D_{kj})
CEM	1.00	5.00	3.00	0.6267
NPE	0.20	1.00	0.25	0.0936
UMS	0.33	4.00	1.00	0.2797

Note: Inconsistency index: 0.0824

Table IV. A sample pair-wise comparison matrix of the elements within the cluster PRP with respect to the control criterion PRO (productivity)

For instance, the pair-wise comparison matrix is formed by comparing the clusters (i.e. decision areas) like product design, PRP, facility and layout, quality control, etc. with respect to the control criterion – productivity. Table V shows the pair-wise comparison for the relative importance of clusters (decision areas) with respect to the control criterion (productivity).

Step 7. Similarly the clusters are again compared with each other with respect to the other control criteria like quality, cost, flexibility, etc. The number of additional matrices formed in this stage will be equal to the number of control criteria and the corresponding eVectors of these matrices are used as P_{ja} values in stage – 5, where j represents the component and a representing control criteria.

In this problem, seven matrices are formed because we have considered seven control criteria. Up to this stage, 77 (70 + 7) matrices in total have been formed.

5.2.3 *Pair-wise comparison at control criteria level.*

Step 8. This step results in forming additional matrix to determine the importance of control criteria with respect to the goal. Again similar to Step 3, pair-wise comparison matrix is formed for the control criteria and using equation (1), the eVectors are calculated. This eVector will be used in Stage 6 for the calculations of weighted index.

Table VI shows the pair-wise comparison matrix for the relative importance of control criteria (competitive priorities) with respect to the goal. The obtained eVectors represents the relative importance of the control criteria with respect to the main goal of the problem. With this additional matrix the total number of matrices has increased to 78.

5.3 *Stage 3: pair-wise comparisons for interdependencies*

To find out the interdependencies between elements in the cluster, which occur in a sub-network of a control criterion, pair-wise comparisons are to be carried out between elements with respect to one of its elements in the clusters under each control criterion.

Table V.
Pair-wise comparison for the relative importance of the clusters (decision areas) with respect to the control criterion (productivity)

	COI	FAL	HRM	MAI	MAN	PPC	PRD	PRP	PUR	QCO	eVector (P_{ja})
COI	1.00	0.14	0.33	0.20	0.25	5.00	2.00	0.20	6.00	0.50	0.0499
FAL	7.00	1.00	5.00	3.00	4.00	6.00	9.00	0.33	5.00	2.00	0.2206
HRM	3.00	0.20	1.00	0.50	1.00	5.00	3.00	0.25	4.00	0.50	0.0742
MAI	5.00	0.33	2.00	1.00	0.33	4.00	3.00	0.50	6.00	0.50	0.0956
MAN	4.00	0.25	1.00	3.00	1.00	6.00	5.00	0.33	7.00	0.25	0.1108
PPC	0.20	0.17	0.20	0.25	0.17	1.00	2.00	0.25	3.00	0.25	0.0289
PRD	0.50	0.11	0.33	0.33	0.20	0.50	1.00	0.20	2.00	0.25	0.0250
PRP	5.00	3.00	4.00	2.00	3.00	4.00	5.00	1.00	7.00	3.00	0.2412
PUR	0.17	0.20	0.25	0.17	0.14	0.33	0.50	0.14	1.00	0.14	0.0172
QCO	2.00	0.50	2.00	2.00	4.00	4.00	4.00	0.33	7.00	1.00	0.1360

Note: Inconsistency index: 0.0907

Step 9. By keeping one of the elements constant, pair-wise comparison is made between other elements in that cluster under the given control criterion. Again similar to Step 3 and using equation (1), pair-wise comparison matrices are formed and the eVectors was calculated. These eVectors will be used to develop the un-weighted super matrix. The number of matrices formed in this step will be equal to the number of elements within the cluster.

In this problem, interdependencies occur between the elements of all of the clusters (shown by looped arc in the Figure 2). For example, in the PRP cluster, the elements CEM and use of multiple small machines (UMS) are related as similar machines have to be grouped into a cell. Hence, pair-wise comparison was carried out within the PRP cluster, between the remaining elements with respect to an element in the same cluster. For instance, Table VII shows the pair-wise comparison of the elements within PRP cluster with respect to UMS and the control criterion – productivity.

Similarly by keeping each element within PRP cluster constant, pair-wise comparison matrices are formed between remaining elements with respect to the control criterion – productivity. Since, three elements are present within the cluster PRP, three matrices will be formed for this cluster alone. The remaining two matrices are not shown here.

Step 10. Repeat Step 9 for pair-wise comparison of elements within the remaining clusters with respect to one of the elements in the cluster and the same control criterion. The number of matrices formed in this stage will be equal to the total number of elements within each cluster with respect to a given control criterion.

For instance, under the control criterion productivity, there are ten clusters (decision areas) and the elements in each cluster are varying.

	COS	DEL	FLE	INN	MOR	PRO	QUA	eVector
COS	1.00	4.00	5.00	6.00	3.00	0.33	0.50	0.1921
DEL	0.25	1.00	2.00	3.00	0.50	0.20	0.20	0.0643
FLE	0.20	0.50	1.00	3.00	0.33	0.25	0.33	0.0561
INN	0.17	0.33	0.33	1.00	0.33	0.20	0.25	0.0348
MOR	0.33	2.00	3.00	3.00	1.00	0.25	0.33	0.0953
PRO	3.00	5.00	4.00	5.00	4.00	1.00	0.50	0.2760
QUA	2.00	5.00	3.00	4.00	3.00	2.00	1.00	0.2811

Note: Inconsistency index: 0.0725

Table VI. Pair-wise comparison for the relative importance of control criteria (competitive priorities) with respect to the goal

	CEM	NPE	eVector
CEM	1.00	5.00	0.833
NPE	0.20	1.00	0.167

Notes: Pair-wise comparison of the elements under the cluster PRP with respect to UMS (use of multiple small machines) and the control criterion – PRO (productivity). Consistency index: 0.000

Table VII.

In total, there are 60 elements, which have been categorized into these ten clusters. Hence, 60 pair-wise comparison matrices for interdependencies are formed just for one control criterion.

Step 11. Similar to Steps 9 and 10, pair-wise comparisons for the interdependencies are again carried out among the elements of all clusters but with respect to the other control criteria. The number of matrices formed at the end of this stage will be equal to the product of number of control criteria and the total number of elements within all clusters. The eVectors from these matrices are used to form the un-weighted "super matrix" for the corresponding control criteria.

In our case problem, at the end of this step, under each control criterion, 60 matrices would have formed. Hence, for the seven control criteria (competitive priorities) considered, 420 matrices will be formed.

5.4 Stage 4: super matrix formation and analysis

Super matrix is used for the resolution of the interdependencies that exist between the components/elements. The super matrix will be used to find the relative stabilized weights of each of the elements/components.

5.4.1 Super matrix formation. The "super matrix" is a matrix with same fields of components/elements (which have interdependencies) as rows and columns. There are three types of "super matrices" that will be formed in this stage:

(1) the un-weighted super matrix, where the entries are taken directly from the eVectors obtained in Stage 3;

(2) the weighted super matrix, where each sub-matrix is multiplied by its weight to make the matrix column stochastic, i.e. the sum of values in each column is made equal to 1; and

(3) the limiting super matrix obtained by raising the weighted super matrix to arbitrarily large powers.

5.4.2 Un-weighted super matrix formation.

Step 12. The rows and columns of the super matrix are the elements of all the clusters. It is denoted by M. The eVectors obtained in Steps 9-11 are the entries for each column. It is formed for each control criterion. Hence, the number of un-weighted super matrix will be equal to the number of control criteria.

For example, under the control criterion – productivity, the entries for the column UMS would be entered from the eVector obtained in Step 9 (refer Table VIII for the values). Similarly other values from other clusters for the given control criterion are entered in the super matrix. In total, seven such un-weighted super matrices are formed one for each of the control criteria (competitive priorities). Since these matrices are 60 × 60 matrices, they cannot be represented as a single table and accommodated in a single page. Hence, we have not shown these matrices considering the space limitations.

5.4.3 Weighted super matrix formation.

Step 13. This step is used only when the un-weighted super matrix is not column stochastic. To check for column stochasticity, sum up the column entries.

Elements	Weight values
CTR	0.11
HOK	0.09
PST	0.04
RSS	0.12
VSM	0.04
WIP	0.10
OPF	0.10
SWP	0.17
USC	0.03
WLB	0.19
CFT	0.04
COE	0.03
EEP	0.03
FOS	0.04
JOE	0.05
JOR	0.04
MFT	0.05
MSW	0.06
RER	0.11
SUS	0.06
AUM	0.08
MAP	0.14
PRM	0.14
SAI	0.14
ANJ	0.10
AUN	0.09
FFP	0.07
MSC	0.03
SMD	0.08
STC	0.04
VIC	0.08
EDI	0.05
ERP	0.07
KAN	0.08
MMM	0.03
PRS	0.11
PUL	0.07
SLP	0.09
CAD	0.04
CEG	0.03
DFM	0.03
DSN	0.05
MDN	0.07
PBD	0.08
UCP	0.09
USP	0.11
CEM	0.23
NPE	0.07
UMS	0.20
FMD	0.06

(*continued*)

Table VIII.
Weight values obtained for each element from the limiting matrix of the control criterion – PRO (productivity)

Table VIII.

Elements	Weight values
ISS	0.06
LSR	0.16
SOS	0.14
STD	0.08
CUF	0.03
DES	0.15
POK	0.20
QUC	0.08
SPC	0.05

If the sum is equal to 1, then it is column stochastic. If the matrix is column stochastic, then proceed to Step 16 else proceed to Step 15.

In the case problem under consideration, the sum of the column entries of the un-weighted super matrix for the control criterion –PRO (productivity) is equal to 1 and hence it is already column stochastic. Hence, Step 15 was not carried out and directly, the limiting super matrix was calculated, which is shown in Step 16. Similarly, the un-weighted super matrices of the remaining control criteria were also column stochastic; hence the weighted super matrices for these control criteria are not developed.

Step 14. If the sum of the column entries in the un-weighted matrix is not equal to 1, then it is not column stochastic. In such cases, each sub-matrix is multiplied by its weight of the cluster to make the matrix column stochastic, i.e. the sum of values in each column is made equal to 1. The obtained matrix is called weighted super matrix. The number of weighted super matrices will also be equal to the number of control criteria.

5.4.4 Limiting super matrix. Since the "un-weighted super matrix" in our case problem is already column stochastic, the "limiting super matrix" is directly calculated:

Step 15. To obtain the limiting super matrix, the weighted super matrix has to be checked for cyclicity. If the weighted super matrix does not have cyclicity, it would be evaluated as $\lim_{x \to \infty} W^k$, where W is the "un-weighted" super matrix, i.e. raise the powers of the weighted super matrix arbitrarily to a large number, until the weights of each element have become stabilized, i.e. all the values in a row are same.

In case of cyclicity, limiting matrix will be formed by using the following formula:

$$\lim_{x \to \infty} \left(\frac{1}{N}\right) \sum_{i=1}^{N} W_i^{\mathrm{k}},$$

where N is the number of "limiting super matrices". The stabilized value in each row is the weight of that element of that component with respect to the corresponding control criteria. This value is used in Stage 5 as

A^{I}_{kja}, where, k representing the element of component j under control criteria a. The number of limiting super matrices formed will be equal to the number of control criteria.

In this case problem, the "un-weighted super matrix" does not have cyclicity and hence the power of the matrix is raised to a large number for getting the "limiting super matrix". In this matrix, the row values tend to be constant (which is the main objective of limiting super matrix) and it represents the weight of that element within the cluster with respect to the governing control criterion. Similarly six more limiting super matrices will be formed for the remaining control criteria. Again, due to the space limitations, all seven limiting super matrices are not shown. However, Table VIII shows the weight values obtained for each element from the limiting matrix of the control criterion – PRO (productivity).

5.5 Stage 5: selection of the best alternative

Step 16. Till now the alternatives have not been analyzed. The eVector values related to alternatives are represented as S_{ikja}.The values for S_{ikja} are obtained from the pair-wise comparison matrix, where the alternatives are compared with respect to an element k of cluster j for the control criteria a. Step 3 along with equation (1) will be used to calculate the eVector for the alternatives for each element of the cluster under each control criterion. The number of pair-wise comparison matrices obtained will be equal to the product of number of elements and number of control criteria.

In our case problem, the alternatives – TMS, CIMS and LMS are compared with each element within the clusters (decision areas) with respect to each control criterion (competitive priorities) to obtain the S_{ikja} values. Table IX shows a sample pair-wise comparison matrix of the alternatives under the element CEM within the cluster PRP with respect to control criterion PRO (productivity). In total, 60 pair-wise comparison matrices will be formed under the control criterion PRO (productivity) alone. If we consider all the seven control criteria, 420 (60 × 7) matrices will be formed.

Step 17. In this step, desirability index for each of the alternatives will be calculated for each control criterion by using the following formula:

Table IX. A sample pair-wise comparison matrix of the alternatives under the element CEM within the cluster PRP with respect to control criterion PRO (productivity)

	CIMS	LMS	TMS	eVector (s_{ikja})
CIMS	1.00	0.50	5.00	0.3255
LMS	2.00	1.00	8.00	0.6044
TMS	0.20	0.12	1.00	0.0701

Note: Inconsistency index = 0.0053

$$D_{ia} = \sum_{j=1}^{J} \sum_{k=1}^{K_{ja}} P_{ja} A_{kja}^{D} A_{kja}^{I} S_{ikja} \tag{2}$$

Where, D_{ia}, desirability index of alternative i under the control criterion a; Here, i, alternatives; a, control criterion; P_{ja}, relative important weight of cluster j on control criteria a, i.e. obtained from the pair-wise comparison matrix for the relative importance of the clusters under control criteria (refer Step 6); A_{kja}^{D}, relative important weight of element k of cluster j of control criteria a, i.e. obtained from pair-wise comparison matrix for elements with in the clusters under a given control criteria (Refer Step 3); A_{kja}^{I}, stabilized weight of element k of cluster j with respect to control criteria a, i.e. obtained from the row entries of limiting super matrix (refer Step 14); S_{ikja}, relative importance of alternative i on the element k of cluster j, with respect to the control criteria a.

Similarly, desirability indices for the alternatives have to be calculated with respect to the other control criteria, which require the algorithm to be repeated again.

For example, a sample desirability index calculation for the alternatives with respect to the control criteria PRO (productivity) is presented. Table X shows the desirability indices for the alternative manufacturing systems under the control criterion – PRO (productivity) along with the corresponding P_{ja}, A_{kja}^{D}, A_{kja}^{I}, and S_{ikja} values.

5.6 Stage 6: calculation of weighted index

Once all the desirability indices for the alternatives are calculated for all the control criteria, the weighted index for the alternative has to be calculated:

Step 18. The weighted index of an alternative i is calculated by using the formula:

$$\mathrm{AWI}_i = \sum_{a=1}^{n} D_{ia} C_a \tag{3}$$

Where, AWI_i, weighted index of the alternative i; D_{ia}, desirability index of alternative i; for control criteria a; which are obtained from Step 16; C_a, relative important weights of control criteria a on the overall objective, i.e. these values are obtained from pair-wise comparison matrix for the relative importance of the control criteria on the overall objective (Step 8, Table VI).

For example, in our case problem, the desirability indices of the alternatives obtained for control criteria PRO (productivity) are CIMS – 0.0307, LMS – 0.0871 and TMS – 0.0155. The relative importance of the control criterion PRO (productivity) is 0.2761. This is multiplied with each of the alternative values. Similarly, the desirability indices of the alternatives with respect to other control criteria and their

Table X. Desirability indices for alternative manufacturing systems under the control criterion – PRO (productivity)

Decision areas	P_{ja}	Elements	(A^D_{kja})	(A^L_{kja})	CIMS (S1)	LMS (S2)	TMS (S3)	CIMS	LMS	TMS
COI	0.0182	CTR	0.5649	0.11	0.1929	0.701	0.1061	0.0002	0.0008	0.0001
	0.0182	HOK	0.2255	0.09	0.1125	0.7089	0.1786	0.0000	0.0003	0.0001
	0.0182	PST	0.0821	0.04	0.1571	0.5936	0.2493	0.0000	0.0000	0.0000
	0.0182	RSS	0.0409	0.12	0.1564	0.745	0.0986	0.0000	0.0001	0.0000
	0.0182	VSM	0.0442	0.04	0.0986	0.745	0.1564	0.0000	0.0000	0.0000
	0.0182	WIP	0.0424	0.10	0.1564	0.745	0.0986	0.0000	0.0001	0.0000
FAL	0.1124	OPF	0.2509	0.1	0.1088	0.7286	0.1626	0.0003	0.0021	0.0005
	0.1124	SWP	0.0925	0.17	0.157	0.5936	0.2493	0.0003	0.0010	0.0004
	0.1124	USC	0.0544	0.03	0.1125	0.7089	0.1786	0.0000	0.0001	0.0000
	0.1124	WLB	0.6022	0.19	0.1169	0.6833	0.1998	0.0015	0.0088	0.0026
HRM	0.1792	CFT	0.1368	0.04	0.1998	0.6833	0.1169	0.0002	0.0007	0.0001
	0.1792	COE	0.0322	0.03	0.1125	0.7089	0.1786	0.0000	0.0001	0.0000
	0.1792	EEP	0.2494	0.03	0.1564	0.745	0.0986	0.0002	0.0010	0.0001
	0.1792	FOS	0.0168	0.04	0.1929	0.701	0.1061	0.0000	0.0001	0.0000
	0.1792	JOE	0.0198	0.05	0.229	0.6955	0.0755	0.0000	0.0001	0.0000
	0.1792	JOR	0.0302	0.04	0.1884	0.7306	0.081	0.0000	0.0002	0.0000
	0.1792	MFT	0.0968	0.05	0.5469	0.3445	0.1085	0.0005	0.0003	0.0001
	0.1792	MSW	0.0702	0.06	0.256	0.6708	0.0732	0.0002	0.0005	0.0001
	0.1792	RER	0.2934	0.11	0.1125	0.7089	0.1786	0.0007	0.0041	0.0010
	0.1792	SUS	0.0544	0.06	0.1088	0.7286	0.1626	0.0001	0.0004	0.0001
MAI	0.0892	AUM	0.234	0.08	0.0726	0.7612	0.1662	0.0001	0.0013	0.0003
	0.0892	MAP	0.5301	0.14	0.1662	0.7612	0.0726	0.0011	0.0050	0.0005
	0.0892	PRM	0.0716	0.14	0.1662	0.7612	0.0726	0.0001	0.0007	0.0001
	0.0892	SAI	0.1643	0.14	0.5736	0.3614	0.065	0.0012	0.0007	0.0001
MAN	0.0793	ANJ	0.062	0.1	0.2227	0.7071	0.0702	0.0001	0.0003	0.0000
	0.0793	AUN	0.3323	0.09	0.784	0.1349	0.0813	0.0019	0.0003	0.0002
	0.0793	FFP	0.1343	0.07	0.1488	0.7854	0.0658	0.0001	0.0006	0.0000
	0.0793	MSC	0.0259	0.03	0.0914	0.691	0.2176	0.0000	0.0000	0.0000
	0.0793	SMD	0.3187	0.08	0.1884	0.7306	0.081	0.0004	0.0015	0.0002
	0.0793	STC	0.0384	0.04	0.1125	0.7089	0.1786	0.0000	0.0001	0.0000
	0.0793	VIC	0.0884	0.08	0.1884	0.7306	0.081	0.0001	0.0004	0.0000
PPC	0.0217	EDI	0.0305	0.05	0.2706	0.6442	0.0852	0.0000	0.0000	0.0000

(continued)

Decision areas	P_{ja}	Elements	(A^D_{kja})	(A^L_{kja})	CIMS (S1)	LMS (S2)	TMS (S3)	CIMS	LMS	TMS
	0.0217	ERP	0.1139	0.07	0.7306	0.1884	0.081	0.0001	0.0000	0.0000
	0.0217	KAN	0.16	0.08	0.1721	0.7258	0.102	0.0000	0.0002	0.0000
	0.0217	MMM	0.0476	0.03	0.6442	0.2706	0.0852	0.0000	0.0000	0.0000
	0.0217	PRS	0.3886	0.11	0.1721	0.7258	0.102	0.0002	0.0007	0.0001
	0.0217	PUL	0.1811	0.07	0.1666	0.7396	0.0938	0.0000	0.0002	0.0000
	0.0217	SLP	0.0783	0.09	0.1125	0.7089	0.1786	0.0000	0.0001	0.0000
PRD	0.0545	CAD	0.288	0.04	0.7853	0.1488	0.0658	0.0005	0.0001	0.0000
	0.0545	CEG	0.0935	0.03	0.2227	0.7071	0.0701	0.0000	0.0001	0.0000
	0.0545	DFM	0.0476	0.03	0.1349	0.7838	0.0812	0.0000	0.0001	0.0000
	0.0545	DSN	0.045	0.05	0.081	0.731	0.188	0.0000	0.0001	0.0000
	0.0545	MDN	0.0237	0.07	0.2227	0.7071	0.0701	0.0000	0.0001	0.0000
	0.0545	PBD	0.0677	0.08	0.2176	0.691	0.0914	0.0001	0.0002	0.0000
	0.0545	UCP	0.1028	0.09	0.3531	0.5861	0.0608	0.0002	0.0003	0.0000
	0.0545	USP	0.3316	0.11	0.1571	0.5936	0.2493	0.0003	0.0012	0.0005
PRP	0.2792	CEM	0.6267	0.23	0.3255	0.6044	0.0701	0.0131	0.0243	0.0028
	0.2792	NPE	0.0936	0.07	0.7418	0.183	0.0752	0.0014	0.0003	0.0001
	0.2792	UMS	0.2797	0.2	0.0789	0.7957	0.1253	0.0012	0.0124	0.0020
PUR	0.017	FMD	0.0844	0.06	0.0986	0.745	0.1564	0.0000	0.0001	0.0000
	0.017	ISS	0.4252	0.06	0.2222	0.6667	0.1111	0.0001	0.0003	0.0000
	0.017	LSR	0.0504	0.16	0.1998	0.6833	0.1169	0.0000	0.0001	0.0000
	0.017	SOS	0.2648	0.14	0.2684	0.6144	0.1172	0.0002	0.0004	0.0001
	0.017	STD	0.1752	0.08	0.2857	0.5714	0.1429	0.0001	0.0001	0.0000
QCO	0.1493	CUF	0.0333	0.03	0.1571	0.5936	0.2493	0.0000	0.0001	0.0000
	0.1493	DES	0.1276	0.15	0.1311	0.6608	0.2081	0.0004	0.0019	0.0006
	0.1493	POK	0.4854	0.2	0.1929	0.701	0.1061	0.0028	0.0102	0.0015
	0.1493	QUC	0.0627	0.08	0.1998	0.6833	0.1168	0.0001	0.0005	0.0001
	0.1493	SPC	0.291	0.05	0.1571	0.5936	0.2493	0.0003	0.0013	0.0005
Desirability index								0.0307	0.0871	0.0155

Table X.

corresponding relative importance values with respect to the goal are multiplied. Finally, all these values are summed up for each of the alternatives, which give the weighted index. In this case, the weighted index of the alternative – LMS was found to be 0.0664, while that of CIMS – 0.0233 and TMS – 0.0118. Table XI shows the weighted indices for alternative manufacturing systems based on the control criteria (competitive priorities).

Step 19. From the weighted index, the normalized weighted index is calculated and the best alternative having the highest value is selected.

Table XI also shows the calculation of normalized weighted index of alternative manufacturing systems. From the calculations shown, it can be seen that the normalized weighted index for alternative "LMS" is the highest. Hence, it is considered as best among the alternatives chosen as it has a significant impact on the competitive priorities of the case organisation.

6. Results and discussion

Commenting about the problems faced by the case organisation, the application of ANP methodology as a decision support system enabled the representatives of the organisation to make an informed decision of selecting LMS as the best manufacturing system from the available alternatives under the given case situation. Indeed, LMS has the ability to provide solutions for most of the problems faced by the organisation. For example, the quality, which has been considered as one of the major problems in the valves, can be improved through the use of specific elements of LM such as pokayoke, defect at the source and successive check system, and on/jidoka, empowerment, etc. Similarly, it can reduce cost, through elements such as small lot production, continuous improvement activities, etc. The above claimed benefits were also supported by Sohal and Egglestone (1994) and Jina *et al.* (1997).

Discussing about the technical aspects, while constructing the ANP model for the problem, the interdependencies were assumed to be present between the elements within a cluster. On the other hand, there are cases, where the elements within one cluster may also affect the elements in other clusters. For example, one of the elements in "continuous improvement" cluster is "cycle time and lead time reduction", which can be achieved through effective workload balancing and standardized work processes. But these elements have been categorised under facilities and layout cluster. Thus, there extends a relationship between an element in a cluster and an element in another cluster.

	Control criteria (competitive priorities)/weights for control criteria							Calculated weights for alternatives	
Alternatives	COS	DEL	FLE	INN	MOR	PRO	QUA	SPW1	NORM
	0.1921	*0.0643*	*0.0561*	*0.0348*	*0.0954*	*0.2761*	*0.2811*		
CIMS	0.0214	0.0071	0.0062	0.0039	0.0106	0.0307	0.0313	0.0233	0.2298
LMS	0.0610	0.0203	0.0177	0.0110	0.0301	0.0871	0.0892	*0.0664*	*0.6542*
TMS	0.0108	0.0036	0.0031	0.0020	0.0054	0.0155	0.0158	0.0118	0.1160
								0.1015	1.0000

Table XI. Weighted indices for alternative manufacturing systems based on the control criteria (competitive priorities)

For the sake of reducing the complexity, this issue was not considered while modelling the hierarchical structure and it was assumed that elements in one cluster do not influence the elements in other cluster. The same problem can be modelled and can also be solved without the above-mentioned assumptions but the number of pair-wise comparison matrices will tend to increase further. In addition to this, a sensitivity analysis can also be carried out to check the effectiveness and efficiency of the decisions, which was not carried out in this paper. It should be remembered that the proposed solution from the ANP is applicable only for the case situation discussed. It cannot be generalised for the remaining industries or other industrial sectors.

7. Conclusions

In this paper, an application of ANP methodology has been demonstrated for selecting LMS based on its impact on the functions or activities (decisions areas) of the operations department. Based on the weighted alternative index and normalized weighted alternative index in Table XI, it was found that LMS is superior in comparison with the available alternative manufacturing systems. It was also evident from this paper that a minor issue regarding ANP is that it cannot be used for very complex problems, which involves more number of control criteria, clusters and elements as the number of pair-wise matrices increases drastically and the time required to perform the ANP data entry to arrive at the solution will also be very high. Hence, it may not be favoured by the practitioners. Though the ANP algorithm is cumbersome and time consuming, it has the benefits of providing a better solution than AHP and other MADM techniques as it takes into account interdependencies. In addition to this, similar to AHP, it can take into account both the quantitative and qualitative factors. Since implementing or selecting a suitable manufacturing system is a strategic decision, the use of ANP in this case was justified as it requires such complex analysis to make an effective decision. Finally, this paper has contributed to the body of knowledge in the following manner:

- In the literature related to ANP, many authors have modelled their problems by restricting the number of elements considered in the category of control criteria, clusters to just three or four. But, in this paper, an attempt has been made to solve a much bigger and complex problem, consisting of more number of control criteria, clusters and elements (seven control criteria, 10 clusters and 60 elements).
- A detailed step-by-step application of the ANP in the field of LM has been demonstrated using a case study. According to the authors' knowledge, no paper is available till now in the literature, in which ANP has been applied or used in the field of LM.

We believe that with the proper implementation of LMS, the case organisation can definitely improve its competitive position in the industry.

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