1.0 INTRODUCTION

1.1 AN OVERVIEW OF MULTI-CRITERIA DECISION-MAKING PROBLEMS

Multi-criteria decision-making (MCDM) problems refer to making decisions in the presence of multiple, usually conflicting criteria or objectives. MCDM problems are common in everyday life. In personal context, a house or a car that one wants to buy may be characterized in terms of price, size, style, safety, comfort etc. In business context, MCDM problems are more complicated and usually of large scale. For example, many companies in Europe are conducting organizational self-assessment programs using hundreds of criteria and sub-criteria as set in the EFQM (European Foundation of Quality Management) business excellence model. Purchasing departments of large organizations often need to evaluate their suppliers/vendors using a wide range of criteria in different area, such as after-sale service, quality management, financial stability, delivery time, rejection percentage etc.

The application domain of MCDM problems are quite widespread, MCDM as a separate discipline has a relatively very short history of about only 30 years. The development of MCDM as a separate discipline is closely related to the advancement of the computer technology. In one hand, the rapid development of computer technology in recent years has made it possible to conduct systematic analysis of complex MCDM problems. On the other hand, the widespread use of computers and information technology can generate a huge amount of information and relevant data that makes MCDM increasingly important and useful in supporting business decision-making processes.

There are calls in early 1970s to develop new methods that can produce consistent and rational results, capable of dealing with uncertainties and providing transparency to the analysis process. In general, there exist two distinctive types of MCDM problems due to different problem settings. One type has a finite number of alternative solutions, while the other has an infinite number of solutions. Normally in problems associated with the selection and assessment, the number of alternative solutions is limited. In problems related to design, an attribute may take any value in the given range. Therefore the potential alternative solutions are infinite. If this is the case, the problem is referred to as multi-objective optimization problem, instead of multi-criteria decision problem. The main focus will be on the problems with a finite number of alternative solutions.

A decision matrix can usually characterize a MCDM problem. Suppose, there is m alternatives to be assessed based on n criteria/attributes, a decision matrix is a matrix with each element $a_{ij}$ being the $i^{th}$ criteria value of the $j^{th}$ alternative. Although MCDM problems can be very different in context, they share the following common features:
a) Multiple criteria/attributes often form a hierarchy

Almost any alternative, such as an organization, an action plan or a product of any kind can be evaluated on the basis of attributes. An attribute is a property, quality or feature of the alternative in question. Some attributes can be broken down into further lower level of attributes, called as sub-attributes or sub-criteria. To evaluate an alternative, a criterion is set up for each attribute. Because of the one to one correspondence between attribute and criteria, sometimes attributes are also referred to as criteria and used interchangeably in the MCDM context. MCDM itself can also be referred to as Multiple-attribute Decision Analysis (MADA) if there are a finite number of alternatives.

b) Conflict among criteria

Multiple criteria usually conflict with each other. For example, while designing a car, the criteria of higher fuel economy may mean a reduced comfort rating due to the smaller passenger space.

c) Hybrid nature

i) Incommensurable units

An attribute or criteria may have a different unit of measurement. In the car selection problem, fuel economy is measured by miles per gallon and price is expressed in terms of rupees or dollars. In many decision-making problems, attributes may even be non-quantitative, such as the safety feature of a car may be indicated in a non-numerical way.

ii) Mixture of qualitative and quantitative attributes

It is possible that some attributes can be measured numerically and other attributes can only be described subjectively. For instance, the price of a car is numerical, while the comfort rating is qualitative.

iii) Mixture of deterministic and probabilistic attributes

For example, in the car selection problem, car price is deterministic and fuel economy can be random. Fuel economy changes depending on the road conditions, traffic conditions, weather etc.

d) Uncertainty

i) Uncertainty in subjective judgments

It is common that people may not be 100% sure while making subjective decisions.

ii) Uncertainty due to lack of data or incomplete information

Sometimes information regarding some attributes may not be fully available or even not available at all.

A real life MCDM problem may consist of hundreds of attributes. The assessment and solution of the MCDM problems may not be conclusive due to lack of information, conflict
among the criteria, uncertainties in the subjective judgment and different preferences among the decision makers.

1.2 EVOLUTION OF THE ANALYTIC HIERARCHY PROCESS

Decision-making is a central activity of all people usually done so automatically that we do not even realize that we are doing it every moment of every day of every year throughout all our lives. This salient and inarticulate approach has worked well for us when humanity was fragmented and individuals and groups of people did what they thought of without having to think of others very much. Today, the world has become more limited and interdependent and many of its resources are becoming scarce and valuable, so that we have to work consciously to choose our important courses of action. We have to justify these actions not only to ourselves but also to others so that we can live in harmony with minimum conflict.

Nearly all of us have brought up the belief that clear-headed logical thinking is our only way to face and solve problems. But experience suggests that logical thinking is not natural to us. Indeed, we have to practice, for a long time, before we can do it well. Since complex problems have so many related factors that the traditional logical thinking usually leads to sequence so tangled that the best solutions cannot be easily obtained. Our present complex environment calls for a new logic – a new way to cope with the myriad factors that affect the achievement of goals and consistency of the judgments that we generally use to draw valid conclusions. The new approach should be justifiable and appeals to our wisdom and good sense. It should not be so complex that only the educated people can use it, but should serve as a unifying tool for thought in general.

The lack of a coherent procedure to make decisions is specially troublesome when our intuition alone cannot help us to determine which of the several options are the most desirable, or the least objectionable and then neither the logic nor intuition are of help. Since we are concerned with real-life problems, we must recognize the necessity for trade-offs to best serve the common interest and to be really useful, this process should also assist in building consensus and reaching to a comprehensive solution. We need a way to determine which objective outweighs the other, both in the near and long terms.

In order to deal with these types of problems, the Analytic Hierarchy Process (AHP) has been developed and widely used to make such decisions [1]. It involves breaking the problem down into finer and finer parts so that one is called upon to give a judgment comparing only a pair of issues at a time. This avoids mixing of too many aspects associated with the problem and not knowing what goes with what to obtain the final answer. However, it does call for one to structure the problem hierarchically with broad understanding of the people and their interests and of the
issues involved. Once one has the structure, it becomes easier to convey to the others the influences driving the decision.

The AHP has a strong appeal to the managers and decision-makers at all levels of the decision-making process. It enables one to include both the strength of feelings as needed to express the judgment and logic and understanding relating to the issues involved in the decision. It combines the multiplicity of judgments in a systematic way so as to obtain the best outcome or mix of actions to be taken. Finally and more significantly, these outcomes are derived in an agreeable way that are in harmony with our intuition and understanding and not forced on us by technical manipulations. There are easy to use software packages that can implement this approach and make decision-making task easier.

In sum, the AHP contributes to solving complex problems by structuring a hierarchy of criteria, sub-criteria and alternatives and by eliciting judgments to develop the priorities. It also leads to prediction of the likely outcomes according to these judgments. The outcome can be used to rank the alternatives, allocate resources, conduct cost-benefit comparisons, exercise control in the system, by evaluating the sensitivity of the outcome to changes in the judgment and carry out planning for the projected and desired features. A useful by-product is the measurement of how well the decision-maker understands the relations among various factors. Although people generally are not consistent, the main concern here is the degree of their inconsistencies.

Good decisions must survive the difficulties and hazards of people and environment. We need to make decisions that are both desirable and survivable rather than simply ones that we best like without regard to how lasting they may be. Predicting outcomes plays an important role in making the choices. To do this well, we can decompose a decision into separate structures involving scenarios of benefits, costs, opportunities and risks and then carefully combine the separate outcomes for the best possible decision.

Decision-making groups need to formalize the agenda and structure the interaction. A process that can unfold the complexity of the issues or problems is much needed and will be particularly useful in group decision-making process. Recognizing the perceptions and stakes can vary among the group members, such a process should also specify how individuals can bargain on specific differences. Finally, it will be desirable to have a measure of the consistency of judgments which the individuals give and which the group settles on. The analytic hierarchy process (AHP) is such a technique to ease out the decision-making process.
1.3 ANALYTIC HIERARCHY PROCESS AS A MULTI-CRITERIA DECISION-MAKING TOOL

Globalization has brought changes to the business environment. Corporate business decision-making now often involves groups that are dispersed globally. Traditional face-to-face meetings are costly and are not the practical means for multiple site organizations. Organizations must now often deal with multiple sites and geographically dispersed business associates and partners. The corporate decision-makers are dispersed across the local offices as well as offices in different countries. Internet technology may be an alternative approach to support the dispersed group decision-making process.

There are basically two types of MCDM methods. The first one is compensatory and the other one is non-compensatory.

a) Compensatory methods

Compensatory methods permit trade-offs between the attributes. A slight decline in one attribute is acceptable if it is compensated by some enhancement in one or other attributes. Compensatory methods can again be classified into the following four sub-groups:

i) Scoring method

The scoring method selects or evaluates an alternative according to its score or utility. Utility or score is used to express the decision-maker’s preference. It transforms the attribute values into a common preference scale such that the comparisons between different attributes become possible. A very popular method in this category is the Simple Additive Weighing method. This method calculates the overall score of an alternative as the weighted sum of the attribute scores or utilities. The analytic hierarchy process (AHP) is another popular method in this category. This method calculates the score for each alternative based on pairwise comparisons.

ii) Compromising method

The compromising method selects an alternative that is closest to the ideal solution. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method belongs to this category. This method first normalizes the decision matrix of a MCDM problem. Then based on the normalized decision matrix, it calculates the weighted distance value of each alternative from an ideal solution.

iii) Concordance method

The concordance method generates a preference ranking which best satisfies a given concordance measure. The Linear Assignment method is one of the examples in this category. In this method, it is believed that an alternative having many highly ranked attributes should be ranked first. The problem that the multi-criteria decision-making
process aims to solve is evaluating a set of alternatives in terms of a number of criteria, which are conflicting in nature. Although this is a practical problem, there are few methods available and their quality is hard to determine.

iv) Evidential reasoning approach

The Evidential Reasoning (ER) approach is the latest development in the MCDM area. It is totally different from the above-mentioned three conventional methods. Instead of describing a MCDM problem with the help of a decision matrix, the ER approach uses an extended decision matrix, in which each attribute of an alternative is described by a distributed assessment using a belief structure. For example, the distributed assessment result for the quality of a car engine can be (Excellent, 60%), (Good, 40%), (Average, 20%), (Poor, 10%) and (Worst, 0%), which means that the quality of the car engine is assessed to be Excellent with 60% of belief degree and Good with 40% of belief degree.

b) Non-compensatory methods

Non-compensatory methods do not permit trade-offs between the attributes. An unfavorable value in one attribute cannot be offset by a favorable value in other attribute. Each attribute must have its own standpoints. Hence, comparisons are made on an attribute-to-attribute basis. The MCDM methods in this category are credited for their simplicity. Examples of these methods include the following:

*Dominance method:* In this method, all dominated alternatives are eliminated. There can be more than one solutions generated by this method.

*Maximin method:* Find the weakest attribute value (minimum) of each alternative and then choose the alternative with the best (maximum) weakest attribute value. The logic is that a chain is as strong as its weakest link. This method is applicable only when the attribute values are comparable with one another, either measured in the same unit or transformed to a common scale.

*Maxmax method:* In contrast to the Maximin method, the Maxmax method selects an alternative by its best attribute value. It is applicable only when the attributes are comparable.

*Conjunctive constraint method:* By setting up a minimum standard for each attribute, the alternative selection or evaluation process is simplified to compare each attribute against the standard. If the standard reflects the decision-maker’s expectations, the obtained solution is the satisfying solution.

*Disjunctive constraint method:* This method evaluates an alternative on its best attribute regardless of all other attributes.
These above-mentioned methods may have their own application domains in which they are reasonable, but they may not be useful for general decision-making purposes.

The Analytic Hierarchy Process (AHP) technique is basically chosen for its ease of use and its successful track records in various organizations to solve different types of complex problems. AHP uses a simple method of pairwise comparison of alternatives against different criteria. AHP is widely applied successfully in a variety of decision-making problems [2]. It provides the decision-makers with a method to indicate the decisions by weighing the evaluation criteria and making pairwise judgments of a set or subset of alternatives. AHP can be used to handle complex situations with tangible, intangible, quantitative, qualitative factors within a multi-criteria decision-making domain. AHP can also support a group of decision-makers to arrive to a consensus. Geometric mean values of the individual judgments can be used to aggregate the group preferences.

AHP is a very easy to use and a powerful MCDM tool. The main advantage of AHP is that the users do not have to understand the intricacy of the complex mathematics behind this technique before they can use it. AHP has therefore been adopted as a successful MCDM tool for various management and technological decision-making problems.

1.4 APPLICATION AREAS OF THE ANALYTIC HIERARCHY PROCESS

The Analytic Hierarchy Process (AHP), since its invention, has been a tool at the hands of the decision makers and researchers and it is one of the most widely used multiple criteria decision-making techniques. Many outstanding papers have been published based on the AHP, they include applications of AHP in different fields such as planning, selection of a best alternative, resource allocations, resolving conflicts, optimization etc. and numerical extensions of the AHP. From the critical review of those research papers, it can easily be seen that most of the AHP-related works fall in the combinations of the following areas:

a) engineering and selection,
b) social and selection, and
c) personal and decision making.

This highlights the utility of the AHP as a decision-making tool in engineering as well as social sectors. Again, various application areas of the AHP can be short listed with respect to certain themes as shown below:

a) Selection,
b) Evaluation,
c) Benefit-cost analysis,
d) Allocation,
e) Planning and development,
f) Priority and rank setting,
g) Decision making,
h) Forecasting, and
i) Medicine and related fields.

It is also observed that the AHP is being predominantly used in the theme area of selection and evaluation. As far as the area of application is concerned, most of the times the AHP has been used in engineering, personal and social sectors.

The researchers in the field of AHP have identified the following application areas of the AHP:

**Economic/Management problems**
- Auditing
- Database selection
- Design
  * Architecture
  * Large-scale problems
- Finance
- Macro-economic forecasting
- Marketing
  * Consumer choice
  * Product design
  * Strategy
- Portfolio selection
- Planning
- Facility location
- Forecasting
- Resource allocation
- Sequential decisions
- Policy/strategy making
- Transportation
- Water research

**Political problems**
- Arms control
- Conflicts and negotiation
- Political candidacy
- Security assessment
- War games
- World influence

**Social problems**
- Behavior in competition
- Education
- Environmental
- Health
- Law
- Medicine
  - * Drug effectiveness
  - * Therapy selection
- Population dynamics
- Public sector

**Technological problems**
- Market selection
- Portfolio selection
- Technology transfer

The review of the part research works brings out an interesting observation that in the earlier phase of usage, the AHP had been predominantly used as a stand-alone tool. As the confidence of the researchers grew with the AHP usage, they started experimenting the combination of the AHP with other techniques. This is only possible due to the flexibility of the AHP to be integrated with different techniques, like Linear Programming (LP), Quality Function Deployment (QFD), Artificial Neural Network (ANN) and Fuzzy Logic etc. This enables the user to extract benefits from all the combined methods and hence, achieve the desired goal in a better way. Thus, it can be concluded that the AHP is a flexible multi-criteria decision-making tool. This flexibility is obvious from the fact that some researchers have even converted the Saaty’s nine-point scale to a convenient five-point scale or even a 100-point scale.

It is also clear that the spread of the AHP usage is truly global. The United States, undoubtedly, is the torchbearer in this field, but the developing countries need to use tools like the AHP for evaluation and selection of the complex economic and social systems from different perspectives of development. AHP applications are also catching on in Asian countries. This may be an indication of the importance that the AHP will gain in near future in the developing countries.
In group decision-making environment, the AHP has been proved to be more beneficial than the other conventional techniques such as the Delphi technique. This proves AHP as a very powerful tool that can be used in place of Delphi like widely applied techniques. The AHP has been used for the evaluation purpose ranging as high as seven levels in the hierarchical structure and it has also been applied to evaluate as large as eighteen alternatives. This certainly proves the versatile nature of the AHP, enabling researchers to arrange the different alternatives according to the requirements of the decision(s) to be taken. The AHP has also been found to be useful in considering the ‘yes-no’ like decisions. These decisions generally involve the ‘benefit-cost’ analyses that are similar to the ‘make-buy’ decisions.

The AHP applications in complex situations may demand the use of professional computer application software. In order to overcome the complexity of the situations, Expert Choice software can be used. Based on the review, the following observations will highlight the course of future AHP applications:

a) AHP is going to be used widely for decision-making purposes.

b) AHP use is rising in the developing countries, which augurs well with the economic development of this block of countries, such as India, China etc.

c) Lots of research is going on in the country like USA. The main focus of application seems to be combining various other techniques with the AHP. This is to take advantage of the versatility of the AHP along with the focused use of the other supporting techniques.

d) Use of software applications will be more to address the issue of complexities arising out of the integrated applications of the AHP and other techniques so as to represent the real life situations.

1.5 REVIEW OF THE PAST RESEARCHES

Saaty [3] investigated a method of scaling ratios using the principal eigenvector of a positive pairwise comparison matrix and showed that \( \lambda_{\text{max}} = n \) is a necessary and sufficient condition for consistency of the matrix, where \( \lambda_{\text{max}} \) is the maximum eigen value and \( n \) is the order of the pairwise comparison matrix. A scale of numbers from 1 to 9 is introduced together with a discussion on how it compares with the other scales. To illustrate the developed theory, it is then applied to some examples for which the answer is known, offering the opportunity for validating the approach. The author extended the discussion to multiple criteria decision-making by formally introducing the notion of a hierarchy, investigating some properties of the hierarchy and applying the eigen value approach to scaling complex problems structured hierarchically so as to obtain an one-dimensional composite vector for scaling the elements falling in any single level of the
hierarchy. It is also pointed out that how the hierarchy serves as a useful tool for decomposing a large scale problem, in order to make measurement possible despite the classical observation that the mind is limited to \(7 \pm 2\) factors for simultaneous comparisons.

Hegde and Tadikamalla [4] reported the use of the analytic hierarchy process (AHP) in solving a facility location problem faced by a large multi-national organization. The problem presented by the authors is that of deciding where to locate the service terminals for the spare parts division of the organization. The AHP is introduced and successfully used to solve the problem. A distinct feature noticed by the authors is that the managers developed a sense of ownership in the findings of the study because the AHP facilitates their involvement at early level and the managers realized the superiority of the AHP in capturing the benefits of intangibles such as the perceived importance of the proximity of the location to the customers. Consequently the findings and conclusions are readily implemented in their business plans.

Saaty [5] summarized the principles and philosophy of the analytic hierarchy process (AHP) giving the background information on the type of measurement utilized, its properties and applications. The AHP generates relative scales of measurement and the measurements of a set of objects on a standard scale can be converted to relative scale measurements through normalization. Thus, the AHP, with its relative measurement, helps to determine the outcome of manipulations based on combining different measurements from a standard scale such as a criteria of benefits and a criteria of costs, both measured in dollars and used to select the best alternative.

Basak [6] highlighted that the decision-making process depends heavily on the ranking of the alternatives, especially in the selection problems. But in the selection of a number of highly preferred alternatives, ranking of the alternatives is sufficient. The author mentioned about the ratio scale \((\pi_1, \pi_2, \ldots, \pi_t)\), proposed by Saaty, for the values of alternatives \((T_1, T_2, \ldots, T_t)\) used in a decision problem. Here, \(\pi_i/\pi_j\) is considered to be the ratio of the priority of \(T_i\) to that of \(T_j\). In that context, the author tested a specific rank ordering of the ratio scale.

Triantaphyllou and Mann [7] mentioned that the membership values of the elements of a fuzzy set are of key importance in any theoretical or practical application of fuzzy set theory. Although there are many methods that evaluate membership values, the method proposed by Saaty, based on a matrix of pairwise comparisons and eigen value theory, is the backbone of many other methods. The authors evaluated the above method by using a forward error analysis approach with the assumption that the true membership values in a fuzzy set are continuous in the interval of \((0,1)\). The results revealed that the eigen value method is dramatically inaccurate even for fuzzy sets with few members.

Forman [8] pointed out that the analytic hierarchy process (AHP) is a very powerful tool for multiple criteria decision analysis. AHP’s flexibility, logical and intuitive appeals and ease of use have led to a growing number of applications in a wide variety of complex situations. An
Attractive and powerful aspect of the AHP is the derivation of priority values from a set of pairwise comparisons entered in the form of a positive reciprocal matrix. Until now, the formulations for the consistency indices are available for complete reciprocal matrices. The author also provided the experimental values of consistency indices for incomplete reciprocal matrices.

Saaty [9] compared the eigenvector method with respect to the logarithmic least square estimate for deriving the priority values and highlighted that the eigenvector method deals with two properties simultaneously, i.e. closeness and order. Together, these two methods belong to the field topology of order. The metric idea of closeness is inadequate to judge what is the good approximation of the data involving order relations. There is usually a condition that relates order in the derived scale to order in the data. This is precisely the kind of condition captured by the eigenvector but not by the logarithmic least square estimate.

Vargas [10] mentioned that the analytic hierarchy process is a theory of measurement for dealing with quantifiable and/or intangible criteria that has found rich applications in decision theory, conflict resolution and in models of the brain. It is based on the principle, that, to make decisions, experience and knowledge of people are at least as valuable as the information they use. Decision applications of the AHP are carried out in two phases, e.g. hierarchic design and evaluation. The design of hierarchies requires experience and knowledge of the problem area and the evaluation phase is based on the concept of paired comparisons. It is also pointed out that the success of the AHP theory is a consequence of its simplicity and robustness.

Triantaphyllou and Mann [11] demonstrated that the original AHP and one of its variants have the potential of reaching to the wrong conclusion under certain situations. The authors also examined the effectiveness of these two methods under the assumption that in reality, the pairwise comparisons take on continuous values. This assumption is made in order to capture the majority of the real world problems. The computational results demonstrate that when the above assumption is made, the AHP and the revised AHP may yield a different ranking of the alternatives than the ranking that will result if the actual relative importance is known. The same results also reveal a dramatic increase in the probability that an incorrect ranking occurs as the number of the involved alternatives increases.

Triantaphyllou [12] proposed an efficient approach for cost effective estimation of the pertinent data. The approach is based on a sequence of successive sensitivity analyses. It is pointed out that a critical issue in all real life decision-making problems is the effective estimation of the pertinent data. Often data are difficult to be estimated with accuracy and too dynamic to allow for a timely estimation. This is the case with most of the environmental, agricultural, maintenance, economic, resource management and manufacturing problems everywhere, specially in the United States. If the input data are not correct, then the decision-making process may cause a problem more severe than the one, which is intended to solve.
Partovi [13] presented a methodology and corresponding model for the strategic selection of processes for benchmarking. The process selection methodology starts with strategic benchmarking which includes situation analysis and product feature analysis. Then the analytic hierarchy process (AHP) technique is employed for relating the product features with the value-chain processes. The proposed methodology is implemented in a manufacturing setting, where the forces that shape the firm’s competitiveness are identified and operationalized and the processes are prioritized for benchmarking. Finally, sensitivity analysis is carried out to determine the robustness of chosen activities with respect to small variations in the weights of the manufacturing objectives. The feedback from the managers who participated in the selection process confirmed the utility of the proposed approach.

Triantaphyllou et al [14] pointed out that one of the most critical issues in many applications of fuzzy sets is the successful evaluation of the membership values. A method based on pairwise comparisons provides an interesting way of evaluating the membership values. The authors also mentioned that the original scale as developed by Saaty might cause severe inconsistencies in many practical decision-making problems. The developed exponential scales seem to be more natural for humans to use in many decision-making problems. Two evaluative criteria are used to examine a total of 78 scales, which can be derived from the two widely used scales. It is also revealed that there is no single scale that can outperform all the other scales. The authors indicated that a few scales are very efficient under certain conditions and therefore, for a successful application of the pairwise comparison based method, the appropriate scale needs to be selected and applied.

Triantaphyllou and Mann [15] reported that in many industrial engineering applications, the final decision is based on the evaluation of a number of alternatives in terms of a given number of criteria. This problem may become a very difficult one when the criteria are expressed in different units or the pertinent data are difficult to be quantified. The analytic hierarchy process (AHP) is an effective approach in dealing with this kind of decision problems. The authors examined some of the practical and computational issues involved where the AHP method is used in various engineering applications.

Lin and Yang [16] established a prototype framework and program to be used by the AHP for machine selection and adopted the expert system concept to establish the program and concept expression in the selection of the relevant parameters. The approach seems to avoid difficult and complex calculations and proposes a more economic and simple solution, the analytic hierarchy process (AHP) method, which is used to assess what type of machine – the FMC, NC machine or conventional machine – is most appropriate for a certain type of parts. The authors recommended that the expert experience has to be surveyed in order to establish a
knowledge base of expert opinions and then the AHP can be applied in the selection of the machine for machining a given part.

Korpela and Tuominen [17] mentioned that demand forecasting is one of the most crucial issues in inventory management as the forecasts form the basis for the planning of production, transportation and inventory levels. The traditional methods used for forecasting include the time series methods and causal approaches. The authors presented an analytic hierarchy process-based approach for demand forecasting. The proposed approach offers many improvements as compared to the traditional methods, such as the possibility to include both tangible and intangible factors in the forecasting process and the ability to make predictions about the future development of various environmental factors.

Das et al [18] demonstrated a very simple system, based on cutting force measurement, to determine the tool condition on-line using the analytic hierarchy process (AHP) method. It is mentioned that a wide variety of on-line tool condition monitoring techniques are developed to the present date and timely decision-making for cutting tool indexing needs a proper method for assessment of the state of the tool on-line. It is shown that the misclassifications made by the developed approach may be due to some effects causing variation of the force signals and except for high cutting speed conditions, the AHP-based monitoring system enables a close estimate of the state of the tools to be made.

Islam et al [19] pointed out that the selection of database model is a vital issue in system design. There is no concrete evidence that a single database model satisfies all the requirements of a complex manufacturing system. Different database models satisfy different manufacturing requirements in varying degrees depending on the desired application. The authors addressed the selection of an appropriate database model for a CIM system using the analytic hierarchy process (AHP) method. Due to the conflicting nature of the criteria, the AHP technique appears to be one of the most effective tools for determining the most appropriate database for a CIM system.

Triantaphyllou and Sanchez [20] presented a methodology for performing a sensitivity analysis study on the weights of the decision criteria and performance values of the alternatives as expressed in terms of various decision criteria. The proposed methodology is demonstrated on three widely used decision-making methods. These are the weighted sum method (WSM), weighted product method (WPM) and analytic hierarchy process (AHP). A number of important issues on sensitivity analysis are formalized and some critical theoretical results are also derived. Finally, a number of illustrative examples and computational experiments illustrate the application of the proposed methodology.

Triantaphyllou et al [21] provided a methodology and reasons of performing a sensitivity analysis while dealing with complex maintenance related multi-criteria decision-making problems. The inherent difficulties of accurately assessing the importance of various maintenance
criteria make the application of sensitivity analysis to be an integral part of the solution process. The results derived by using the proposed methodology can enhance and improve the understanding of the dynamics of a complex maintenance problem. All experts agree that the better the understanding of the problem, the more successful a solution can be. The proposed methodology provides some of the means for achieving this goal for maintenance problem solving.

Salo and Hamalainen [22] applied multi-attribute value theory as a framework for examining the use of pairwise comparisons in the analytic hierarchy process (AHP) and indicated that the pairwise comparisons should be understood in terms of preference differences between the pairs of alternatives. The authors demonstrated that the AHP can be modified so as to produce results similar to those of multi-attribute value measurement and proposed the new balanced scales to improve the sensitivity of the AHP ratio scales. It is shown that the so-called super matrix technique does not eliminate the rank reversal phenomenon, which can be attributed to the normalizations in the AHP method. It is also emphasized that the decision makers must understand that both the structure of the hierarchy and the criteria weights need to reflect the set of decision alternatives and their differences.

Ghodsypour and O’Brien [23] commented that the supplier selection is a multi-criteria decision-making problem, which includes both the qualitative and quantitative factors. In order to select the best suppliers, it is necessary to make a trade-off between these tangible and intangible factors, some of which may conflict with each other. When capacity constraints exist, this problem becomes more complicated as, in these circumstances, managers should decide about two problems, i.e. which suppliers are the best and how much should be purchased from each selected supplier. The authors proposed an integration of the analytic hierarchy process and linear programming to consider both tangible and intangible factors in choosing the best suppliers and placing the optimum order quantities among them such that the total value of purchasing (TVP) will become maximum. The proposed methodology can be applied to supplier selection problems with and without capacity constraints. A numerical example is also presented and the model advantages are discussed.

Trentesaux et al [24] developed a decision support system (DSS) for dynamic task allocation in a distributed structure for flexible manufacturing systems (FMS). The characteristics of a DSS that supports multi-criteria (MC) algorithms and sensitivity tests are also presented. The developed DSS is linked to each decision system of every integrated management station (IMS) and it aims at allocating tasks in a dynamic way by proposing a selection of possible resources to the human operators. The developed system increases the ability to integrate random events such as urgent orders or breakdowns by providing an effective dialogue with the operator who certainly owns extra information on the state of the production structure.
Kim [25] emphasized that the Intranet has clear potentials to provide necessary tools for building virtual organizations, which are essential in the present day mass-customization economy. The main objectives of the study are to construct an analytic structure of the Intranet functions and measure the relative importance of those functions. In order to achieve such objectives, a hierarchical structure of the Intranet functions is built based on interviews with the industry experts. Next, using the analytic hierarchy process (AHP) technique, surveys are conducted with three different groups of people, i.e. top management, middle management and low management of the organization. Results from these surveys indicate that several Intranet functions are evaluated as unanimously more important, while others are perceived with varying degrees of importance depending upon the organizational level. The study concludes with the implications of the results to the development of the Intranet systems.

Drake [26] introduced the analytic hierarchy process (AHP) into undergraduate and postgraduate student projects to finalize the process of selection of ‘hard’ and ‘soft’ system components. This formal framework provides greater insight into the student’s reasoning and reveals the extent to which the student understands the objectives of the engineering exercise being tackled and the relative merits of the alternative solutions. It is also pointed out that the AHP makes the selection process more transparent and this is of great benefit in an education and training environment since it reveals in detail a student’s thought.

Labib et al [27] attempted to develop a model of maintenance decision-making using the analytic hierarchy process (AHP) and described problems in maintenance arising from non-availability of data regarding the relevant criteria and robust decisions which will help in maintaining the failing equipment. A dynamic and adaptable maintenance system is developed that utilizes the existing data and supports the decisions accordingly. The authors proposed a three-stage system that can handle multiple criteria decision analysis, conflicting objectives and subjective judgments. The proposed methodology facilitates and supports a group decision-making process and this systematic and adaptable approach will determine what specific actions to perform under given current working conditions. The first stage of the proposed methodology involves identifying the criteria upon which the engineering personnel wish to formulate a maintenance decision or action plan. The second stage is to prioritize the different criteria by implementing a multiple-criteria evaluation method. Finally, based on different criteria, machines are ranked according to criticality, followed by an analysis of failures in a graphical and a hierarchical format.

Triantaphyllou et al [28] discussed some of the challenges faced by the practitioners and theoreticians in multi-criteria decision-making (MCDM) theory. Although it is doubtful that the perfect MCDM approach will ever be found, it is always a prudent idea for the user to be aware of the main controversies in this field. The authors pointed out that the main problem is that often
nobody can know what is the optimal alternative and it is highlighted that the operations research (OR) approach can provide a systematic framework for dealing with such problems.

Robins [29] pointed out that the analytic hierarchy process (AHP) is a method in which clusters of criteria and alternatives are compared a pair at a time to obtain the relative weights. A ratio of relative importance is assigned to each paired comparison, usually according to a ratio scale. Although the method is used in some quarters, there are a number of issues related to the methodology that are hotly debated in the academic literature. The author highlighted some conditions for the successful application of the AHP and mentioned that if the conditions are generally satisfied, the AHP can provide a reasonable response to a selection problem and chose the best alternative.

Koksal and Egitman [30] presented an application of Quality Function Deployment (QFD) for improving the education quality at the Industrial Engineering (IE) Department of Middle East Technical University (METU). The stakeholder groups are identified as the students, faculty members and employers. The use of AHP and the corresponding geometric mean process enabled better handling of different stakeholder groups in the prioritization of their requirements. The authors provided a strong initiative to consider teaching and counseling, and curriculum design for improvement and observed that the awareness of quality has increased and communication has improved in the department, and the industry-department relations has also been enhanced. A house of quality matrix is constructed to determine the IE education stakeholder requirements and translate them into main education design requirements.

Saaty and Hu [31] reported that the eigenvalue method (EM) is the only approach for deriving the priority vector from a pairwise comparison matrix, particularly when the matrix is inconsistent. In the context of multi-criteria decisions, even if variability in ranks does not occur for each individual judgment matrix, it may still occur in the overall ranking of the final alternatives due to the multi-criteria process itself. Because all other proposed methods, like the logarithmic least square method (LLSM), can give different rankings, they are unacceptable for deriving priorities in decision-making as they do not capture the essential idea of transitivity.

Badri [32] offered two approaches to the location selection problem, i.e. an AHP approach and a combined AHP and GP modeling approach and showed that the AHP approach can bring consistency to the location selection process. The author presented a methodology to show how multiple criteria can be combined with the AHP approach to permit a more flexible and inclusive use of the available data about the alternative locations in a location-allocation decision. The author also illustrated how the AHP-based weightage values can be combined in a goal-programming (GP) model to include resource limitations in the location-allocation decision process. It is concluded that the combined AHP-GP method offers a systematic approach to the location-allocation decision problem.
Muralidharan et al [33] mentioned that a single decision maker or a group of decision makers can perform vendor rating using the analytic hierarchy process (AHP) method. The proposed methodology involves estimation by a group or an individual basis following the principle of anonymity. A control chart is constructed with an upper control limit and a lower control limit. Implementation of this control chart takes into account the dynamic nature of vendor performance and it can also be used for continuous monitoring of the vendor performance. The developed procedure can be used for a single vendor as well as for multiple vendors rating.

Kuo et al [34] developed a decision support system using the fuzzy set theory being integrated with the analytical hierarchy process. The proposed system consists of four components, e.g.

(i) hierarchical structure development for fuzzy AHP;
(ii) determination of the weights;
(iii) data collection; and
(iv) decision making.

The model evaluation results, based on 7-ELEVEN joined retailing system, showed that the proposed system is able to provide very good solutions, both in terms of accuracy and speed for the top managers. Moreover, the proposed system can be computerized and it can provide the users a very friendly environment, thus improving its usability.

Poh and Ang [35] carried out a comprehensive study for alternative fuels used for land transportation in Singapore. A multiple attribute analysis is adopted to identify a number of fuel options for possible future use. Analytic hierarchy process-based analysis is performed so as to evaluate four possible plans or scenarios, e.g. status quo, oil and electric vehicles, oil and natural gas vehicles and methanol vehicles. The preferred plan, however, deviates from the most likely future scenario and an iterative forward and backward AHP planning process is then applied to identify and evaluate a set of policies that may be used to reduce the gap.

Yaman and Balibek [36] summarized various facility layout problems, solution requirements and the related decision analysis. The authors provided the steps for decision-making of a common layout problem and analyzed and revised the developed approaches for the solutions according to their decision-making structures. The modular structure of a decision-making support system for a layout problem is outlined and an example of the developed approach is cited. The authors also described the relations between the decision-making strategies and concluded that the proposed approach is quite successful for given types of facility layouts.

Dweiri [37] presented a distinct methodology to develop a crisp activity relationship chart (CARC), based on fuzzy set theory and pairwise comparison of Saaty’s analytical hierarchy process (AHP), which ensures the consistency of the designer’s assignments of importance of one factor over another so as to find the weight of each of the factors in every activity. The author
developed a computer program, FUZZY, based on the AHP and the fuzzy decision-making system (FDMS) is used to generate the CARC. It is also pointed out that the new methodology of developing CARC has many advantages over the traditional method of generating the activity relationship chart (ARC).

Saaty [38] mentioned that the Analytic Network Process (ANP) is a general theory of relative measurement as used to derive composite priority ratio scales from individual ratio scales that represent relative measurements of the influence of elements which interact with respect to the control criteria. Through its super matrix whose elements are themselves matrices of column priorities, the ANP captures the outcome of dependence and feedback within and between the clusters of elements. The analytic hierarchy process (AHP) with its dependence assumption on clusters and elements is a special case of the ANP. The ANP is a new and an essential phase in decision-making, neglected so far because of its linear structures used in traditional approaches and their ability to deal with feedback in order to chose alternatives no simply according to attributes and criteria, but also according to their consequences both positive and negative – an essential and so far a missing consideration in decision-making.

Triantaphyllou [39] mentioned that although the pairwise comparisons are seen by many as an effective and intuitive way for eliciting qualitative data for multi-criteria decision-making problems, a major drawback is that the number of the required comparisons increases quadratically with the number of the entities to be compared. Thus, often data for medium size decision problems may be impractical to be elicited using the pairwise comparisons. The more the comparisons are, the higher is the likelihood that the decision maker will introduce erroneous data. The author introduced a dual formulation to a given multi-criteria decision-making problem that can significantly alleviate the previous problems. Some theoretical results establish the fact that this can only be possible when the number of alternatives is greater than the number of decision criteria plus one.

Ray and Triantaphyllou [40] highlighted that a critical problem in decision analysis is how to evaluate the difference between two or more different rankings of a set of alternatives. It is assumed that a group of decision makers has already established a ranking for each one of a set of alternatives. The authors examined how to evaluate the differences among these rankings and mentioned that this problem does not have a unique solution. It is also pointed out that this problem is not trivial and, moreover, it is associated with some counter-intuitive issues. It is shown that for a given problem, where the number of alternatives m and the number of decision criteria n are given, the number of all possible rankings is not equal to m! as one may have expected, but it is a function of m and n and it can be significantly less that m!.

Ossadnik and Lange [41] evaluated the quality of three software products, i.e. AutoMan, ECPro and HIPRE 3+, supporting the Analytic Hierarchy Process and employed the results of the
evaluation to generate paired comparisons which are integrated into an AHP-based decision model. The relevant criteria of this model are derived from the international norm ISO/IEC 9126. Consequently, the decision problem ‘choice of a suitable AHP-software’ is shown with an AHP-based decision model for some selected software alternatives. The evaluation of the tested software indicated that the local priorities could generally be found, whereas the final rank order of the alternatives depends on the individual weights of the criteria. Finally, the authors provided a way to present both, a better transparency of the operative capability of the AHP and a generally applicable method to evaluate the AHP-software.

Karapetrovic and Rosenbloom [42] highlighted that the analytic hierarchy process (AHP) requires a specific consistency check of the pairwise comparisons in order to ensure that the decision maker is being neither inconsistent nor random in his or her pairwise comparisons. However, there are many situations where the decision maker is reasonable, logical and non-random in making the pairwise comparisons and yet will fail the consistency check. The authors argued against the use of the standard consistency check and recommended a quality control approach for checking the consistencies of the pairwise comparison matrices.

Lee and Kim [43] mentioned that the information system (IS) project selection are basically multi-criteria decision-making (MCDM) problems. Existing methods for IS project selection do not reflect interdependencies among various criteria and candidate projects. Considering these interdependencies among the criteria provides valuable cost savings and greater benefits to the organizations. While evaluating the project selection problems, the authors collected a group opinion to know the interdependence relationship among various criteria. In order to collect group opinion for interdependent project problems, the authors used expert interview. The authors also suggested an improved IS project selection methodology that will reflect interdependencies among various evaluation criteria and candidate projects using the Analytic Network Process (ANP) within a zero-one goal programming (ZOGP) model.

Bevilacqua and Braglia [44] described the application of the analytic hierarchy process (AHP) for selecting the best maintenance strategy for an important Italian oil refinery. Five possible alternatives are considered, e.g. preventive, predictive, condition-based, corrective and opportunistic maintenance. The best maintenance policy must be selected for each facility of the plant. The machines are clustered in three homogeneous groups after a criticality analysis based on the internal procedures of the oil refinery. With the AHP technique, several aspects that characterize each of the considered maintenance strategies are arranged in a hierarchic structure and evaluated using a series of pairwise judgments. To improve the effectiveness of the developed methodology, the AHP is coupled with a sensitivity analysis.

Ong et al [45] mentioned that the analytic hierarchy process (AHP) uses established procedures to capture the best rank from the judgments, through the weighting and synthesizing
of the decision process and develops a hierarchy, that is compatible with a network having various dependencies. It compares the alternatives, one at a time, in the context of priorities. The authors used the AHP method to derive a single environmental score based on process emissions for each of the products or alternatives evaluated. Based on these environmental scores, the products can be ranked with respect to their environmental merits. Then the AHP method is incorporated into the pre-LCA tool to assign accurate environmental scores to the products. The developed AHP model is applied to a case study, which is a comparative study of polystyrene and porcelain plates and the results showed that the developed methodology is able to provide sound evaluation procedure.

Byun [46] explored the use of the analytic hierarchy process (AHP) for deciding on car purchase and highlighted that it is important to include the elements that will provide attributes to make consumer decision-making easier, comfortable and therefore, lead to a car purchase. As the car market becomes more competitive, there is a greater demand for innovation that will provide better consumer service and strategic competition in the business environment. The author presented a new methodological extension of the AHP by focusing on two main issues. The first one combines pairwise comparisons with a spreadsheet method using a 5-point rating scale and the other one applies the group weight to a reciprocal consistency ratio check. Three newly formed car models of medium size are used to show how the proposed method allows the choice to be prioritized and analyzed statistically.

Chuang [47] combined the Analytic Hierarchy Process (AHP) and Quality Function Deployment (QFD) techniques to support a facility location decision from a requirement perspective. The proposed approach begins with identifying the location requirements, followed by the derivation of the location evaluating criteria. The AHP is used to measure the relative importance weightage values for each location requirement. The importance degree and the normalized importance degree of each location criteria are then computed using the QFD transformation for constructing the facility location model. The AHP is used to assess the evaluating score of each candidate location for each particular location criteria. Finally, an overall score for each of the candidate locations is computed for the decision-maker to select the optimal location. An example is also cited to demonstrate how the proposed approach works.

Kodali and Chandra [48] described a multi-attribute decision model using the analytic hierarchy process for the justification of total productive maintenance (TPM) in Indian industries. The authors pointed out that TPM can bring in commendable reforms and improvement in terms of equipment effectiveness, better product quality and meeting promised delivery dates and conductive work places. The obtained results are quite significant and promising and the derived priorities can be very useful for strategic and operational decisions in reallocating resources.
Badri [49] identified five sets of quality measures and these measures or indicators are then accurately and consistently weighted through the analytic hierarchy process. The priority weights are, in turn, incorporated in a goal-programming model to help in selecting the best set of quality control instruments used for customer data collection purposes. The author also proposed a decision aid that will allow weighting of a firm’s unique service quality measures, consider the real world resource limitations and select the optimal set of service quality control instruments. The author addressed two important issues, i.e. how to incorporate and decide upon quality control measures in a service industry and how to incorporate the AHP into the model. The author also illustrated a real world case study using the application of this combined analytic hierarchy process and goal-programming (AHP-GP) model.

Alvi and Labib [50] identified the present trends in manufacturing and mentioned that it is necessary to define methodologies for manufacturing that are capable of identifying the driving forces of change and coping with the resultant changes. Some manufacturing paradigms are proposed and investigated. The characteristics and enabling methodologies of those paradigms are also discussed. The criteria that justify a suitable manufacturing paradigm for the twenty-first century are presented in a hierarchy model based on the analytic hierarchy process (AHP). The developed decision tool is used to identify the paradigm with the highest ranking for future implementation. A sensitivity analysis is also performed to observe the effects of varying the priorities of different criteria.

Forman and Gass [51] noted that the exposition on the analytic hierarchy process (AHP) has the following objectives, e.g.

(i) to discuss why the AHP is a general methodology for a wide variety of decision and other applications;
(ii) to present brief descriptions of successful applications of the AHP; and
(iii) to elaborate on academic discourses relevant to the efficacy and applicability of the AHP vis-à-vis competing methodologies.

The authors discussed about the three primary functions of the AHP, i.e. structuring complexity, measurement on a ratio scale and synthesis, as well as the principles and axioms underlying these functions. Two detailed applications of the AHP are also presented.

Braglia et al [52] presented a new multi-criteria decision model for the material handling device (MHD) selection problem in cellular manufacturing systems. Given a set of manufacturing cells based on several automatic work centers, the technique makes it possible to select a particular MHD for each cell in an integrated way, with different constraints being taken into consideration. The approach is based on two different multi-attribute analyses executed with the analytic hierarchy process (AHP) and a final integer linear programming including important
limitations faced by the designer while making the MHD investment decisions. An example using real life data is also cited to illustrate the effectiveness of the developed methodology.

Proll et al [53] described the improvements to the sensitivity analysis algorithm, together with the technological improvements in the computing environment that will make the linear and bilinear models viable in the near real time. In order to improve the current algorithm and its implementation, the authors investigated, on the one hand, an opportunistic approach aimed at reducing the number of optimization problems solved in the original framework and on the other hand, an alternative framework based on distance analysis. Computational results on linear and bilinear models are also reported.

Triantaphyllou [54] demonstrated through some numerical examples that the ranking abnormalities are possible even when the data are perfectly known (and thus perfectly consistent). Therefore, it can very well be the case that the decision maker may never know the exact ranking of the alternatives in a given multi-criteria decision-making problem when the original AHP or its current additive variant are used. An extensive computational study and examination of 22 real life case studies randomly taken from the open literature demonstrated that these ranking abnormalities might occur dramatically often. The author also proved that these ranking irregularities are not possible when a multiplicative variant of the AHP is used.

Chan et al [55] mentioned that the material handling equipment selection is a complex and tedious task and there are very few tools other than checklists to assist the engineers in the selection of appropriate, cost-effective material handling equipment. The authors developed an intelligent material handling equipment selection system, called as Material Handling Equipment Selection Advisor (MHESA). The MHESA is composed of the following three modules, e.g.

a) a database to store equipment types with their applications;

b) a knowledge-base expert system for assisting material handling equipment selection; and

c) an analytic hierarchy process (AHP) model to choose the most favorable equipment type.

The proposed concept can automate the design of a material handling equipment selection system and provide artificial intelligence in the decision-making process.

Yang and Shi [56] proposed the analytic hierarchy process (AHP) as an emerging solution approach to large, dynamic and complex real world multi-criteria decision-making problems, such as the strategic planning of organization resources and justification of new manufacturing technology. The authors presented an application of the AHP in organization’s long-term overall performance evaluation through a case study in China. An effective evaluation of the organization’s overall performance is a key step for the long-term strategic planning process. The results of the case study showed that such an AHP application could assist managers to effectively evaluate the organization’s overall performance in the long-term strategic planning process even under complex economic and marketing conditions.
Lai et al. [57] reported the results of a case study where the analytic hierarchy process (AHP) technique is employed to support the selection of a multi-media authorizing system (MAS) in a group decision-making environment. Three MAS products are identified and ultimately ranked using the AHP technique. Six software engineers, who are technically competent and experienced, participated in the study. A post-study survey and interview are conducted with all the engineers to collect further feedback on the use of the AHP, as compared to the frequently used Delphi technique, in supporting group decisions. The experimental results and survey findings indicated that the AHP is preferred to Delphi as the AHP helps the group members to center a discussion on the objectives, rather than the alternatives. It is also observed that the AHP is more conductive to consensus building in group decision settings.

Lipovetsky and Conklin [58] considered a pairwise comparison matrix of the analytic hierarchy process (AHP) as a contingency table that helps to identify the unusual or false data elicited from a decision maker. Special techniques are also suggested for robust estimation of the priority vectors that include transformation of a Saaty’s matrix to the matrix of shares of preferences and solving an eigen value problem designed for the transformed matrices. The authors also introduced an optimizing objective that produces robust priority estimation. Numerical results are compared using the AHP with those differing approaches. The comparison demonstrated that the robust estimations yield priority vectors not prone to influence of possible errors among the elements of a pairwise comparison matrix.

Khasnabis et al. [59] developed a performance assessment tool for Michigan transit agencies that receive operating assistance from the Michigan Department of Transportation (MDOT) and also presented the application of two techniques, i.e. Analytic Hierarchy Process (AHP) and Goal Achievement Technique (GAT) for evaluation of one of the five peer groups specially created for the project. It is pointed out that both the AHP and GAT are viable tools for conducting transit performance assessment. Both of them are capable of using a wide range of performance data and developing a composite performance index for each transit agency. The authors, however, recommended the AHP as a better multi-criteria assessment tool because of its stronger mathematical foundation, its ability to gauge consistency of judgments and flexibility in the choice of ranges at the sub-criteria level.

Handfield et al. [60] illustrated the use of the analytical hierarchy process (AHP) as a decision support model to help managers understand the trade-offs between environmental dimensions, and also demonstrated how the AHP can be used to evaluate the relative importance of various environmental traits and assess the relative performance of several suppliers along those traits. Three case studies are carried out so as to demonstrate the benefits and weakness of using the AHP in this field. Finally, it is examined that how the AHP can be incorporated into a comprehensive information system supporting environmentally conscious purchasing (ECP).
Hafeez et al [61] provided a structured framework for determining the key capabilities of an organization using the analytic hierarchy process. One distinctive characteristic of the developed framework is that quantitative (financial) as well as qualitative (non-financial) measures are employed providing a balanced scorecard for the capability evaluation. The framework is illustrated using a manufacturing organization as an example. The analysis may be viewed as a benchmarking exercise in order to find the competency gaps within the organization. The results obtained are to be exploited by the organization so as to undertake strategic investment decisions such as capability development, outsourcing, focusing on diversification with regards to new products, services or markets. The framework is generic in nature and applicable to benchmark a public or service sector organization.

Chin et al [62] investigated the critical factors and sub-factors that determine the adoption and implementation of TQM in the state-owned enterprises (SOEs) and foreign joint ventures (FJVs) in China with particular reference to the Shanghai manufacturing industries. An analytic hierarchy process (AHP) approach is employed to prioritize the relative importance of four critical factors and sixteen sub-factors among the SOEs and FJVs in China. These enterprises will stress on the soft TQM factors of organizing, culture and people rather than on the hard factors of the systems, techniques, measurement and feedback. Top management commitment, leadership, education and training are among the most important sub-factors. The results suggest a generic hierarchy model for the organizations to prioritize the critical factors and formulate strategies for implementing TQM in Shanghai as well as other cities and regions in China.

Chu and Liu [63] reported that since Saaty presented his famous research on the Analytic Hierarchy Process, many followers have tried to extend the knowledge of this new and growing branch of operations research. At the same time, some opponents have raised several questions to improve this novel category. Among them, they questioned why the consistency ratios should be \( \leq 0.10 \). The authors studied the mathematical formulations behind the consistency ratio and urged the researchers to use the criteria of consistency ratios of 0.10.

Korpela et al [64] proposed a framework by which the risks related to a customer-supplier relationship, the service requirements by the customers and the strategies of the supplier organization could be included in the production capacity allocation and supply chain design. The developed approach provides a systematic and flexible framework for solving production allocation problems that will maximize the strategic importance of the customers, minimize customer related risks, and in addition, maximize the preferences of the customers. Compared to the traditional cost and profit based approaches for production allocation, this approach will make it possible to take into account both qualitative and quantitative factors for solving the problem. Traditionally, the focus is on the organization’s own quantitative viewpoints, but this approach will enable focusing on the customers viewpoints. Finally, it is pointed out that the proposed
approach will form a basis for evaluating the production allocation problem on the tactical decision-making level.

Lee [65] addressed the problem of aggregating individual opinions into group consensus under group decision-making environment. The author employed a simple similarity measure to deal with the situation when the opinions are disjoint. The principle of optimality is defined and an iterative approximation algorithm is proposed. The author also considered the degree of importance of each expert and showed that the proposed aggregation method preserves the important properties of other aggregation methods.

Basak [66] discussed how the model-selection procedures such as Akaike’s information criteria (AIC) can be used for selecting the most appropriate one out of several existing statistical models in the literature for the judgment data as used in analytic hierarchy process (AHP). Furthermore, once the appropriate model is selected, a procedure is proposed on the basis of AIC for statistical ranking of the alternatives. This ranking procedure does not suffer from the problem of intransitivity and is based on non-normal distributions. It also enables one to obtain the detailed pattern for the ordered priorities of the alternatives in the decision-making process involving the AHP.

Beynon [67] mentioned that the analytic hierarchy process (AHP) introduced by Saaty is a well-known and popular method of multi-criteria decision-making. Central to this method are the pairwise comparisons between the criteria and decision alternatives made using a 9-unit scale. The author contrasted the appropriateness of the 1-9 scale with other alternative 9-unit scales as also used in the AHP, by looking at the probability distributions of the associated priority values. For large problems, estimated probability distributions are found for the priority values using the method of Parzen Windows.

Yu [68] extended the practical applications of the analytic hierarchy process (AHP) to tackle a broader range of fuzzy problems by developing a separable linear expression so as to represent general triangular, concave, convex and concave-convex mixed vague ratings. Since the developed solution algorithm is simple and the problem solution methodology is distinct, a user-friendly computer program can be easily developed to handle simple yet time-consuming linearization calculations. Moreover, many prevailing software packages like LINDO or EXCEL can conveniently compute the formulated models. As a result, the generated priority vector of the proposed method allows the decision maker to perform sensitivity analysis. Hence, the proposed method is a promising and attractive alternative to the current fuzzy AHP methods.

Forgione et al [69] provided separate ratings for artificial intelligence and decision support system journals, reviewed the criteria and adopted the AHP methodology to evaluate decision-making support system journal quality. Next, the authors performed an updated discussion of the data collection process and the resulting multiple criteria evaluation. The authors
also presented an informative system to consistently deliver the methodology to the researchers, academic administrators and practitioners in a transparent manner. The paper concludes with a summary of the evaluation and implications for information system theory and practice.

Kuo et al [70] pointed out that the conventional approaches to location selection can only provide a set of systematic steps for problem-solving without considering the relationships between the decision factors globally. The authors aimed to develop a decision support system for locating a new convenience store (CVS). The proposed system consists of the following four components, e.g.

a) hierarchical structure development for fuzzy analytic hierarchy process (fuzzy AHP),

b) weights determination,

c) data collection, and

d) decision making.

In the first component, reviewing the related references and interviewing the retailing experts can formulate the hierarchical structure of the fuzzy AHP. Then, a questionnaire survey is conducted to determine the weight of each factor in the second component, while the corresponding data are collected through some government publications and actual investigations. Finally, a feed forward neural network with error back-propagation (EBP) learning algorithm is applied to study the relationship between the factors and the store performance. The study showed that the proposed approach is able to provide more accurate results than the regression models.

Das and Chattopadhyay [71] applied the analytic hierarchy process (AHP) to estimate the state of the cutting tool during machining of a medium carbon steel work piece with coated carbide inserts. Three components of cutting forces are used to judge whether the tool is sharp, workable or worn out. It is observed that the estimated state of tool wear matches closely with the directly observed state of the tool wears. Thus, the AHP can be applied successfully to estimate the state of tool wear condition.

Saaty [72] showed that the principal eigenvector is a necessary representation of the priorities derived from a positive reciprocal pairwise comparison judgment matrix. When providing numerical judgments, an individual attempts to estimate sequentially an underlying ratio scale and its equivalent consistent matrix of ratios. Near consistent matrices are essential because when dealing with intangibles, human judgment is inconsistent and if with new information, one is able to improve inconsistency to near consistency, then that can improve the validity of the priorities of a decision. In addition, judgment is much more sensitive and responsive to large rather than small perturbations and hence, once near consistency is attained, it becomes uncertain which coefficients should be perturbed by small amounts to transform a near consistent matrix to a consistent one. If such perturbations are forced, they can be arbitrary and thus distort the validity of the derived priority vector in representing the underlying decision.
Yang and Kuo [73] proposed an analytic hierarchy process (AHP) and data envelopment analysis (DEA) based approach to solve the plant layout design problem. A computer-aided layout-planning tool is used to generate a considerable number of layout alternatives as well as to generate quantitative decision-making unit (DMU) outputs. The qualitative performance measures are weighted by the AHP and DEA is then applied to identify the performance frontiers leading to the final candidate layout alternatives. Large numbers of design alternatives are evaluated efficiently to avoid the entrapment of a local optimum or an inferior solution. Empirical illustrations from a practical case study illustrated the effectiveness of the proposed methodology.

Xu et al [74] applied the analytic hierarchy process (AHP) framework to assess and compare the optimum edible film for kiwifruits. With the mathematical model on the permeability of edible films and using the analytical hierarchy process, four items including the permeability of oxygen, carbon dioxide and water vapor, and respiratory quotient of edible films used for kiwifruit preservation are evaluated comprehensively. The optimum edible film composed of soybean protein isolate (SPI), stearic acid (SA) and pullulan (Pul) is obtained and used to preserve kiwifruits. The formulated AHP model can also determine the weights of the related edible films with great accuracy.

Saaty et al [75] mentioned that an intangible is an attribute that has no scale of measurement. Intangibles such as effort and skill arise in conjunction with resource allocation, but are not usually included directly in a mathematical model because of the absence of any unit of measurement. However, intangibles can be quantified through relative measurements or priorities and intangible resource allocation uses these priorities along with the normalized measures of tangibles in a linear programming model with coefficients and variables measured in relative terms. The priorities of tangible resources from the optimal solution can then be used to assign monetary values to the priorities of the intangible resources.

Bodin and Gass [76] discussed about various aspects of the analytic hierarchy process (AHP) that are important to the successful presentation of the AHP to graduate business students. The authors created a working paper that presents some of the examples and class projects that are found to be of pedagogical value. It is also pointed out that the teaching of the AHP is relatively straightforward and can be covered in about 2-3 weeks of class time in MBA level. Because of these time restrictions, the instructor must be comprehensive and well organized with the Expert Choice (EC) examples worked out in advance.

Laininen and Hamalainen [77] reported that in the analytic hierarchy process (AHP), the decision maker makes comparisons between pairs of attributes or alternatives and in real applications, these comparisons are subject to judgmental errors. Many AHP-matrices are found to be such that the logarithm of the comparison ratio can be sufficiently well modeled by a normal standard distribution with a constant variance. The authors presented the formulae for the
evaluation of the standard deviations of the estimates of the AHP-weights obtained by regression analysis. In order to eliminate the effect of an outlier in the comparison ratios, a robust regression technique is elaborated and compared with the eigenvector method and the logarithmic least square regression technique. A dissimilarity matrix approach is also presented for the statistical simultaneous comparisons of the AHP-weights and the results are illustrated by simulation experiments.

Ong et al [78] described a fuzzy set-based manufacturability evaluation system that assesses the manufacturability of features on a part through the generation of manufacturability indices (MIs). The methodology incorporates design and related machining issues. Compared to existing rule-based approaches, the proposed approach is based on the fuzzy set theory. Fuzzy set representation and reasoning are used in the selection of the required support methods and operation types and also in the generation of MIs. The adoption of MIs rather than cost or time to measure manufacturability makes the system more efficient since no process details are needed to generate those indices. It gives the system the advantage of providing a more comprehensive measurement metric since cost, time and other factors affecting the economics of machining a part are merged into the MIs. This system is expandable and upgradable. The feature-based model can be extended to include other part families if different types of feature representation schemes are used.

Saaty and Ozdemir [79] demonstrated that in making preference judgments on pairs of elements in a group as it is done in the analytic hierarchy process (AHP), the number of elements in the group should be no more than seven. The reason is found in the consistency of information derived from the relations among the elements. When the number of elements increases past seven, the resulting increase in inconsistency is too small for the mind to single out the element that causes the greatest inconsistency to scrutinize and correct its relation to the other elements, and the result creates confusion to the mind from the existing information. The authors also proposed that as the inconsistency measurement is relatively small, improving inconsistency requires only small perturbations and it will be hard for the decision maker to determine what that change should be, and how such a small change can be justified for improving the validity of the outcome. The mind is sufficiently sensitive to improve large inconsistencies, but not small ones and the implication of this is that the number of elements in a set should be limited to seven plus or minus two.

Aguaron and Moreno-Jimenez [80] suggested that the row geometric mean method (RGMM), one of the most extended AHP’s prioritization procedures, is a measure of the inconsistency based on the stochastic properties of a subjacent model. The authors formalized this inconsistency measure, hereafter called as the geometric inconsistency index (GCI) and provided
the thresholds associated with it. These thresholds allow an interpretation of the inconsistency tolerance level analogous to that as proposed by Saaty.

Dey [81] highlighted that the present method of pipeline health monitoring, which requires an entire pipeline to be inspected periodically, is both time wasting and expensive and presented a risk-based model that reduces the amount of time spent on inspection. The proposed model not only reduces the cost of maintaining petroleum pipelines, but also suggests an efficient design and operation philosophy, construction methodology and logical insurance plan. The risk-based model uses the analytic hierarchy process (AHP), a multi-attribute decision-making technique, to identify the factors that influence failure of the pipeline on specific segments and to analyze their effects by determining the probability of the associated risk factors. The severity of failure is determined through the consequence analysis. From this, the effect of a failure caused by each risk factor can be established in terms of cost and the cumulative effect of failure is determined through probability analysis. The developed model does not totally eliminate subjectivity, but it is an improvement over the existing inspection method.

Zio et al [82] illustrated a systematic methodology to guide the definition of the failure criteria of a passive system and the evaluation of its probability of occurrence, through the identification of the relevant system parameters and propagation of their associated uncertainties. Within this methodology, the authors proposed the use of the analytic hierarchy process as a structured and reproducible tool for the decomposition of the problem and identification of the dominant system parameters. The practice of supporting the AHP procedure with sensitivity analysis seems to be a potentially fruitful one for achieving greater robustness in the results. The proposed methodology is applied for assessing the reliability of an existing thermal hydraulic passive system of reference and it can also be used to estimate the influence of the governing parameters during the design phase of new projects.

Malik and Sumaoy [83] analyzed a feeder-specific expansion investment plan of a distribution utility for exploiting the demand-side resource options using feeder and time-specific marginal costs and observed that with a utility-led demand-side management program where the utility shoulders the up-front capital and administrative costs while the benefits are equally shared between the utility and participating customers, idle customer-owned standby diesel generating sets together with efficient cooling and lighting technologies appear as a viable option to meet the current and projected demand. Demand-side resources prioritization based on their impact to monetary and non-monetary criteria (reliability, voltage quality, environmental etc.) is accomplished with the analytic hierarchy process (AHP) technique. The customer’s perception to each of the given decision criteria are solicited through customer survey.

Mikhailov [84] proposed a new approach for deriving priorities from fuzzy pairwise comparison judgments, based on $\alpha$-cuts decomposition of the fuzzy judgments into a series of
interval comparisons. The assessment of the priorities from the pairwise comparison intervals is formulated as an optimization problem, maximizing the decision-maker’s satisfaction with a specific crisp priority vector. A fuzzy preference programming method, which transforms the interval prioritization task into a fuzzy linear programming problem, is applied to derive the optimal crisp priorities.

Condon et al. [85] demonstrated that a multi-dimensional scaling technique, known as the Sammon map, could be used to visualize the judgments of a group of decision makers using the analytic hierarchy process. Sammon maps are constructed for an actual problem that is modeled using the AHP by a government agency. The judgments of eight decision makers for six pairwise comparison matrices are visualized in 18 different Sammon maps. The maps are easy to construct and also easy to read and interpret. These types of maps can be generated in real time, so that the outlier participants can be questioned immediately about their judgments. In this way, each decision maker will be encouraged to make comparisons that reflect true opinions that are not distorted. It is also pointed out that this type of visualization tool can be applicable in a wide variety of group decision-making environments such as assisting in Delphi studies.

Al-Najjar and Alsyouf [86] assessed the most popular maintenance approaches including strategies, policies and philosophies, using a fuzzy multiple criteria decision-making (MCDM) methodology. Two examples are cited to show how the suggested evaluation methodology identifies the most informative approach. Using the fuzzy MCDM, it is possible to select, in advance, the most informative/efficient maintenance approach. Consequently, this leads to less planned replacements and the failures can be reduced to approximately zero and higher utilization of component life can be achieved. Thus, the maintenance department can contribute to the business objectives through effectively participating and adding value to the production related activities.

Saaty and Ozdemir [87] illustrated that how negative priorities can be defined as relative numbers and used along with the positive priorities. The authors indicated that in decision-making, it is not necessary or possible to parallel each positive or negative priority by creating its opposite value. The effect of negative priorities is discussed so as to show how to synthesize the priorities obtained from benefit, opportunity, cost and risk hierarchies. Several ways of synthesis are given that can be applied in different situations. One can use all or select one method that suits one’s understanding best. If the rankings are different with the methods, the information needs to be considered. It is finally pointed out that each of the positive or negative priorities need not have a symmetric opposite value, because the opposite criteria may not exist in practice.

Wasil and Golden [88] pointed out that the analytic hierarchy process (AHP) is widely used to rank, select, evaluate and benchmark a wide variety of decision alternatives. Over the last 25 years, thousands of AHP applications are cataloged, categorized and annotated in edited
volumes and books, in journal articles and on Web sites. The AHP is used by the organizations in both the public and private sectors to deal with complex problems. For more than two decades, the AHP is the part of the curriculum covering decision-making techniques in business and engineering schools. Operations research practitioners around the world have repeatedly embraced the AHP as a methodology that can produce insightful results to difficult real-world decision problems.

Korhonen and Topdagi [89] investigated the performance of the analytic hierarchy process (AHP), when the utility of the objects cannot be evaluated on the same ratio scale. The basic assumption in the AHP is that a decision maker compares objects on a ratio utility scale. However, there are situations in which the AHP is used even if the basic assumption is violated. This kind of problem occurs, when a decision maker is asked to compare, for instance, object(s) he likes to the object(s) he hates. In this case, the performance of the AHP is expected to be very poor, because each object the decision maker likes is presumably ‘absolutely better’ than any object(s) he hates. It is also pointed out that comparing gains and losses ruins the AHP analysis. However, the results demonstrated that the AHP is able to estimate the reasonable utility values for objects surprisingly well.

Nigim et al [90] applied the analytical hierarchy process (AHP) to determine the impact of special protection scheme (SPS) failures in a power system. The application of the AHP reduces time and effort in locating the most and least vulnerable SPS as it integrates an expert’s service experience in the field and the other probability tools. Its major advantage is that persons who have little field experience can use it. The 179-bus Western States Coordinating Council (WSCC) system is chosen as the power system to illustrate the application of the developed technique. Each generator site is assumed to be equipped with a SPS that is capable of tripping the generation. The objective is to study the impact of SPS mal-operations due to hidden failures at the most critical bus location. Such failures usually cause the most severe problems. This bus or site can then be a candidate for installation of redundant supervisory control measures in an attempt to avoid the worst-case scenarios.

Stam and Pedro Duarte Silva [91] took a close look at the multiplicative ratings method, which has recently received growing attention. The interest in the multiplicative AHP (MAHP) is motivated by the fact that, in contrast with the original AHP, it precludes certain types of rank reversals as the composite priority ratings continue to follow a ratio scale, even after normalization. The authors derived and discussed several interesting properties of the MAHP that have eluded attention in previous studies and also argued that these properties of the MAHP are interesting not only for mathematical reasons, but also on behavioral grounds. The authors also showed how the AHP offers a more flexible preference modeling framework, while still preserving the ratio scales property, by relaxing the ‘constant returns to scale’ assumption as made
in the previous researches. The authors also used simulation experiments to explore the extent to which the theoretical differences between the original AHP (additive AHP) play out computationally for various different types of preference structures, enabling to assess whether the MAHP is merely an interesting theoretical construct, or can in fact make a substantial difference in terms of rankings and ratings of the alternatives and rank reversals between the alternatives.

Fogliatto and Albin [92] proposed a new method for sensory data collection and analysis based on analytic tools from Saaty’s AHP, magnitude estimation procedures and scoring scales as used in Quantitative Descriptive Analysis techniques. The method yields quantitative data, that can be used for model building purposes and generates an efficiency measure for subjects such as the consistency ratio. Using the consistency ratio, the efficiency of different subjects may be taken into account while combining their evaluations into a single vector. The use of the proposed method is illustrated in two case studies. The first one is from a food industry that seeks to find a new formulation for a product. The second one is from a plastic industry and its goal is to find an appropriate warranty policy for a product that degrades over time.

Yedla and Shrestha [93] examined the impact of including various qualitative criteria for the selection of alternative transportation options in Delhi. Three alternative transport options, i.e. 4-stroke 2-wheelers, CNG cars and CNG buses are prioritized based on six different criteria, e.g. energy saving potential, emission reduction potential, cost of operation, availability of technology, adaptability of the option and barriers to implementation. Integrated quantitative and qualitative criteria gave a contrasting result as compared to that of the conventional quantitative and qualitative approaches with highest priority for CNG buses followed by 4-stroke 2-wheelers and CNG cars. This can explain the reasons for failure of many potential alternative urban transport options.

Sarkis [94] showed how a generalized analytical hierarchy technique based on Saaty’s systems with feedback approach, also known as the analytical network process (ANP), can be applied as an alternative methodology. The proposed approach can be completed through the utilization of a super matrix that can arrive at a solution where the necessary combined weights of the factors influencing the performance measure are the results. It is also pointed out that the ANP approach can be used so as to enhance the dynamic nature of the manufacturing strategy performance evaluation model.

Kwiesielewicz and Uden [95] introduced a new approach to measure the consistency, inconsistency and contradictory of judgment matrices obtained as the results of the pairwise comparisons in the AHP. The proposed approach can easily be applied for the case with many expert opinions and it is logical to check the judgments independently and exclude the
contradictory opinions. The approach can also be extended for fuzzy opinions. Finally, an algorithm for checking contradictions is presented.

Yurdakul [96] presented a strategic justification tool for machine tool selection. With the developed tool, the evaluation of investment in machine tools can model and quantify the strategic considerations. Both the AHP and ANP techniques are applied in calculation of the contributions of machine tool alternatives in the manufacturing strategy of an organization. Hierarchical design structures are formed in the application of the AHP and ANP approaches. Ranking scores that are used to rate the alternatives are obtained as the outcomes of these applications. Application of the ANP approach also enables the incorporation of interdependencies among the components of the decision structures. An illustrative example is also provided and the organization management found the application and the results satisfactory and implementable in their machine tool selection decisions.

Liberatore and Nydick [97] pointed out that in the application of the analytic hierarchy process, a wash criterion is the one where all the alternatives are equally preferred with respect to that criterion. In the case where the wash criterion is a sub-criterion, the effect of removing it from the hierarchy is also addressed. Eliminating an important sub-criterion may affect the importance of the criteria of which it is a part. If a wash criterion is eliminated, the pairwise comparisons with respect to that criterion must be reassessed. After reassessment, the overall rank order of the objects may or may not be affected by excluding the wash sub-criterion. If the criteria are not reassessed, the wash sub-criteria should not be eliminated.

Topcu [98] proposed a multi-criteria decision model for construction contractor selection in the Turkish public sector. Current selection methods are reviewed and three main concepts are generated for selection, i.e. cost, time and quality. The proposed selection model uses evaluation criteria related to these concepts and has a process with the following two main stages, e.g.

a) contractor prequalification, and

b) choice of the eligible bidder among the prequalified contractors.

The project owners can test the developed model as a decision support system in order to identify an eligible contractor to be awarded with the contract.

Tsai and Hsiao [99] presented a method to translate the customer needs into applicable alternative combinations for the products of customer’s desire and utilized the theory of the analytic hierarchy process (AHP) to evaluate the importance of the customer needs which are generally rated and described by qualitative expressions. A fuzzy inference model is employed to establish the relationship between the customer needs and alternatives for a multi-functional product. Then a fuzzy synthetic distance method is used to perform optimal searching for the possible alternative combinations in the product. Based on the proposed methods and associated algorithms, a consultative interface is setup on the Internet for a case study to demonstrate its
effectiveness. Although a baby stroller is taken as an example in this study, this method can also be applied to other products.

Mikhailov [100] proposed a new method for group prioritization in the analytic hierarchy process (AHP), based on a fuzzy programming optimization approach that maximizes the group satisfaction with the final group solution. The group fuzzy preference-programming (GFPP) method combines the synthesis and prioritization stages into a single integrated stage, it can deal with missing decision maker’s judgments and provide an appropriate index for measuring the consistency of the group solution. The method is very attractive from the computational point of view, requiring the solution of only one single linear program. All these features make the proposed method a suitable alternative to the existing group prioritization methods used in the AHP. The method can easily be embedded in a decision support system to support group decision-making situations and it will provide an easier way to obtain the group’s priorities.

Venkata Rao [101] presented a strip-layout selection procedure pertaining to metal die stamping work in complex layout situations. The proposed procedure is based on the AHP method and it helps in selecting a suitable strip-layout from amongst a large number of available strip-layouts for a given metal stamping operation. The methodology is capable of taking into account all the important requirements of metal stamping and it strengthens the existing procedure by proposing a logical and rational method of strip-layout evaluation and selection.

Yurdakul [102] mentioned that in order to select the best set of CIM alternatives among the competing ones, it is necessary to make a trade-off between the quantitative and qualitative factors, some of which may conflict. Selection of the appropriate CIM alternatives is vital in manufacturing organization’s long-term competitiveness and it requires development of suitable selection models. The selection model must consider various quantitative and qualitative objectives and constraints simultaneously. For example, the manufacturing organizations may have generally limited funds to invest in new advanced technologies. The size of the allocated fund limits the types and number of CIM alternatives that an organization can select in a given time period. The author proposed a combined model consisting of the analytic hierarchy process and goal programming to consider multiple objectives and constraints simultaneously. A real life example is also provided so as to illustrate the application of the combined approach.

Chakraborty and Banik [103] mentioned that strategic planning in the area of maintenance related problems are one of the most complex and ill-structured tasks often faced by the manufacturing organizations. The maintenance planning and control task involves a large extent of unknown and multiple criteria with uncertain long or short-term outcomes. Therefore, adopting the best course of action from a set of alternatives to achieve the desired objective is the prime interest of the maintenance department. The authors focused on the objective of providing the professional engineers and industrial managers with the basic understanding of the use of the
AHP technique for selecting the optimal maintenance policy so as to make the best uses of the available resources for reliable performance of the plant while minimizing the total maintenance cost.

Chakraborty and Banik [104] explained the problem of selection of the ideal vendor in a given organizational situation that involves the multi-criteria decision-making process. The proposed approach begins with identifying the criteria, sub-criteria and the related hierarchy that affect the selection of the ideal vendor. A central relationship matrix is established to display the degree of relationship between each pair of judgment and the AHP technique is used to measure the relative importance of each criterion. Finally, the overall score with respect to each criterion is computed to select the ideal vendor in order to meet the organizational requirements. A real time example is also cited to demonstrate the usefulness of the AHP-based vendor selection approach.

Escobar et al [105] analyzed the consistency in group decision-making for the analytic hierarchy process (AHP). While using the weighted geometric mean method (WGMM) as the aggregation procedure, the row geometric mean method (RGMM) as the prioritization procedure and the geometric consistency index as the inconsistency measure, it is proved that the inconsistency of the group is smaller than the largest individual inconsistency. Moreover, the authors also pointed out that by using the RGMM prioritization procedure, the group priorities obtained through the aggregation of the individual priorities verify the requirement of consistency proposed in the AHP methodology if the individual priorities also verify this requirement.

Enea and Piazza [106] pointed out that the selection of a project among a set of alternatives is a difficult task the decision makers have to face. Difficulties in selecting a project arise because of the different goals involved and because of the large number of attributes to consider. The authors proposed a project selection approach based upon a fuzzy extension of the analytic hierarchy process. The authors focused on the constraints that have to be considered within fuzzy AHP in order to take in account all the available information. It is also demonstrated that by considering all the information deriving from the constraints, better results in terms of certainty and reliability can be achieved.

Bala Chandran et al [107] presented an approach based on linear programming (LP) that estimates the weights for a pairwise comparison matrix generated within the framework of the analytic hierarchy process. The authors applied the LP approach to several sample problems and compared the results to those produced by other widely used methods, like the eigen value method (EM) and logarithmic least square (LSS) method. In addition, the authors also extended the developed linear program to include applications where the pairwise comparison matrix is constructed from interval judgments.

Millet and Schoner [108] described why and how ratio scaled multiple criteria analysis techniques, such as the Analytic Hierarchy Process (AHP), should allow for a subtraction
mechanism whereby negative preference is combined with positive preference. The main contribution of the authors is a demonstration of how the current imposition of a strictly positive additive value structure can lead to incorrect preference ratios and even incorrect ranking of the alternatives. The proposed preference elicitation and computation method solves these problems in a simple and intuitive manner.

Ramanathan [109] proposed the application of data envelopment analysis (DEA) to generate local weights of the alternatives from pairwise comparison judgment matrices used in the analytic hierarchy process (AHP). The author also explained the underlying assumption behind this approach and explored some silent features. It is proved that DEA correctly estimates the true weights when applied to a consistent matrix formed using a known set of weights. DEA is further proposed to aggregate the local weights of alternatives in terms of different criteria to compute the final weights. It is also proved that the proposed approach, called DEAHP does not suffer from rank reversal when an irrelevant alternative(s) is added or removed.

Pi and Low [110] highlighted that the purchasing function directly affects the competitive ability of a firm. Purchasing managers need to periodically evaluate supplier performance in order to retain those suppliers who meet their requirements. The importance of incorporating multiple attributes, such as quality, on-time delivery, price and service into vendor evaluation are well established. The authors provided a more accurate and easier method for quantifying the supplier’s attributes to quality-loss using a Taguchi loss function and these quality losses are also transferred into a variable for decision-making by the analytical hierarchy process (AHP). An example for supplier evaluation and selection is also presented to demonstrate the functional application of the model.

Liu and Hai [111] mentioned that supplier selection is received extensive attention in supply chain management and illustrated a new approach based on the use of Saaty’s analytic hierarchy process (AHP) method that is developed to assist in multi-criteria decision-making problems. In order to decide the total ranking of the suppliers, the authors compared the weighted sum of the selection number of rank vote, after determining the weights in a selected rank. The authors also presented a novel weighting procedure in place of AHP’s paired comparison for selecting suppliers. It provides a simpler method than AHP that is called voting analytic hierarchy process, but which does not lose the systematic approach of deriving the weights to be used and for scoring the performance of suppliers.

Hartvigsen [112] considered the problem of finding weights that well represent a set of pairwise multiplication comparisons of a set of objects. A method is developed to derive such weights that take into consideration not only the strengths of the pairwise comparisons, but also their directions. The author also presented a set of reasonable axioms for which the proposed method is the unique solution. The method reduces to solving a linear program. It is also
mentioned that the method is quite simple and reduces to performing a forward pass as in the critical path method.

Chakraborty and Banik [113] mentioned that selection of suitable material handling equipment for typically specified conditions and handling environment is found to be a multi-decision making problem for having enhanced material handling effectiveness. The selection procedure for such equipment is found to be unstructured, characterized by extensive domain dependent knowledge base and requires the application of an effective and efficient multi-criteria decision-making tool, like the analytic hierarchy process (AHP). The authors focused on the application of the AHP technique in selecting the optimal material handling equipment under specific handling environment. The relative importance of each criteria, sub-criteria and sub-sub-criteria as considered for selecting the material handling equipment are measured using the pairwise comparison matrices and finally, the overall ranking of each alternative equipment is determined. The authors also performed the sensitivity analysis studies to search out the most critical and robust criteria in the material handling equipment selection process.

Chakraborty and Banik [114] pointed out that the selection of measuring instruments is one of the most complicated decisions to be taken by the manufacturing and quality control departments of an organization. The selection process is mostly affected by the measuring range, accuracy and precision of the instruments. The authors considered three most important criteria, e.g. technical capability, cost and quality awareness along with other sub-criteria, related to the problem, to select the best alternative among the most accurate, more accurate and less accurate type of measuring instruments. The developed approach uses pairwise comparison matrices of analytic hierarchy process (AHP) to determine the priority values of different criteria, sub-criteria and alternatives.

Vaidya and Kumar [115] presented a literature review of the applications of the analytic hierarchy process (AHP), which is being used in almost all the applications related to decision-making. The authors critically analyzed some of the papers published in the international journals of high repute and gave a brief idea about many of the referred publications. Papers are categorized according to the identical themes and also on the basis of the areas of applications. The references are also grouped region-wise and year-wise in order to track the growth of the AHP applications. To help readers extract quick and meaningful information, the references are summarized in various tabular formats and charts. A total of 150 application papers are referred and 27 of them are critically analyzed. It is hoped that the work will provide a ready reference on the AHP and act as an information summary kit for the researchers and practitioners for their future works.
1.6 OBJECTS AND SCOPE OF THE PRESENT RESEARCH

From the survey of literatures and review of the past researches that have been conducted within the available time constraints, it is clear that the analytic hierarchy process (AHP) technique has been successfully applied to various fields of engineering, technology and management studies. The application domain of the AHP includes selection of benchmarking operation, machine selection, inventory forecasting, tool wear monitoring, selection of database models in computer integrated manufacturing (CIM), supplier selection, dynamic task allocation, facility layout selection etc. Some researches have also been done regarding the use of AHP in engineering education and curriculum design. Various authors have also proposed different scales for pairwise comparison of judgments. Other mathematical techniques like fuzzy set theory, artificial neural network, goal programming, 0-1 integer programming have also been incorporated along with the original AHP to widen its applicability. Some researchers have stressed on the application of Saaty’s 1-9 scale for pairwise comparisons, while others have even criticized the use of Saaty’s original scale. The analytic hierarchy process (AHP) has even been used to compare and judge the available AHP-software. Hence, it can be observed that although the AHP technique has been implemented in various fields of engineering and management studies, there is a wide scope of its use in various other areas involving multi-criteria decision-making problems. The popularity of the AHP lies in its simplicity and flexibility in use. So, in the present research work, a maiden venture is taken to apply this simple mathematical technique in various fields of Industrial Engineering (IE) where an optimal solution is to be sought under diverse conflicting situations. Thus, the basic objectives of the present research work lie within the domain of Industrial Engineering (IE) and are enlisted as given below:

(a) to apply the analytic hierarchy process (AHP) for performance evaluation and selection of vendors involving multiple criteria and conflicting alternatives. Five important performance criteria, like technical capability of the vendors, price quoted by the vendors for the required materials, quality of the supplied materials, delivery schedule for the materials and other factors affecting the performance of the vendors are selected so as to rate and rank the vendors engaged in a manufacturing organization. A real time case study is also cited to demonstrate the usefulness of AHP based multi-criteria performance evaluation and vendor selection approach.

(b) to identify the dominant criteria and sub-criteria and their interrelations within the hierarchy that will affect the selection of the optimal maintenance policy for a typical manufacturing organization. Three alternative maintenance policies, like preventive maintenance (PM), corrective maintenance (CM) and condition-based maintenance (CBM) are considered, evaluated and compared with respect to maintainability, maintenance cost, quality and
safety and down time criteria by eliciting judgments for decision-making. The AHP technique is then used to measure the relative importance of each criteria and sub-criteria and finally, the overall score for each alternative is computed to select the optimal maintenance policy in order to fulfill the organizational requirements.

(c) to highlight a distinct methodology to analyze the ‘A’, ‘B’ and ‘C’ class of inventory items using pairwise comparison matrices of the analytic hierarchy process (AHP), which ensures the consistency of the decision maker’s judgments regarding the importance of one criteria over another to find out the weight for each of the considered criteria and sub-criteria. The developed approach is illustrated using real time data and validated with the theoretical results. The AHP technique is used to derive the relative scale of judgments from a standard scale and perform the subsequent mathematical analyses to classify all the inventory items into ‘A’, ‘B’ and ‘C’ categories from the point of view of total consumption value.

(d) to focus on the application of the AHP technique in selecting the optimal material handling equipment under specific handling environment. The relative importance of each criteria, sub-criteria and sub-sub-criteria as considered for selecting the material handling equipment are measured using the pairwise comparison matrices and finally, the overall ranking of each alternative equipment is determined. Sensitivity analysis studies are also performed to search out the most critical as well as robust criteria in the material handling equipment selection process.

(e) to utilize the analytic hierarchy process (AHP) to evaluate the best policy of inventory control. The most important criteria and sub-criteria affecting the selection of the optimal inventory control policy are searched out and their respective priority values are determined imposing the AHP methodology. Five most popularly used inventory control policies including perpetual review policy, periodic review policy, two bin policy, material requirement planning system and optional replenishment policy are considered and then subsequently ranked using the AHP under a multi-criteria environment. These considerations together with the pairwise comparison matrices and evaluating methodology lead to prioritize the conflicting criteria for selecting the optimal policy. Sensitivity studies are also performed to search out the most critical and robust criteria in the inventory control policy selection problem.

(f) to describe the application of the AHP technique for the evaluation and selection of the optimal replacement policy, which is a multi-criteria decision-making problem under constrained environment. Three alternative policies, i.e. unit, block and group replacements are considered and compared with respect to technological, economical and social factors by eliciting judgments for decision-making. The AHP technique is then used to measure the relative importance of each criterion and finally, the preference value of each alternative is
determined so as to select the optimal replacement policy in order to meet the organizational requirements.

(g) to present a comprehensive approach using the analytic hierarchy process to solve the layout design problems considering interdependence among various criteria affecting the selection process. Activity relationships and closeness ratings among the departments of the layout are considered while solving the problem. Finally, a set of alternative layouts is evaluated using the proposed approach. The layout index values measure the priorities of the alternatives to help in selecting the optimal facility layout design.

(h) to consider the three most important criteria such as technical capability, cost and quality awareness along with the other sub-criteria so as to select the best alternative among the most accurate, more accurate and less accurate type of measuring instruments. The developed approach uses pairwise comparison matrices of the analytic hierarchy process (AHP) to determine the priority values of different criteria and sub-criteria. It acts as a decision aid that will allow proper weighting of the customer taste and requirement and helps the decision maker to select the best measuring instrument for a given situation.

(i) to employ the analytic hierarchy process (AHP) to support the decision for selection of an optimal facility location. Four alternative facility locations are considered and then ranked using the AHP technique so as to select the best alternative. It is observed that this technique is more conducive to multi-criteria decision-making problems for selecting the best alternative. It is also noticed that in the AHP, the decision makers develop senses of judgment eliciting expert opinions and thus, the AHP technique facilitates their involvement at every level of the decision-making process. The AHP exercise begins with competitive selection strategies for defining relative importance of the considered criteria, like construction cost, transportation cost, technology, environment, government policy etc. for long run profitability of an organization. These considerations, together with the evaluation methodology, lead to the proposed approach of prioritizing the conflicting criteria for selecting the optimal facility location.

(j) to select the best project from a set of suggested competing alternatives once they are evaluated according to different criteria. Interdependency among the criteria also helps in providing valuable information regarding the selection of the best project. A comprehensive list of objective measures is proposed using analytic hierarchy process (AHP) considering various qualitative factors to evaluate the optimal project selection methodology. Sensitivity study is also performed to check the consistency of judgments.

(k) to develop an application software based on the concept of the analytic hierarchy process (AHP) to aid the multi-criteria decision-making process. The AHP-based application software is developed in Visual Basic (version 6.0). Different criteria, sub-criteria and
alternative decision options related to a specific problem are the inputs to this software. Saaty’s original 1-9 scale for relative measurement is also provided along with the software to help in constructing the pairwise comparison matrices. The application software will develop the relevant hierarchical structure, compute the priority values from the pairwise comparison matrices, check the consistency of the judgments, highlight the most inconsistent element in the comparison matrix, calculate the priority values of the alternatives and finally, select the optimal alternative from the set of alternative decision options. During the development phase, the ease of use of the software is kept in mind. Various error-trapping mechanisms, like the maximum and minimum number of inputs, maximum and minimum number of alternatives, sequence of ‘Ok’ and ‘Next’ buttons etc. are provided with the corresponding message boxes so that the user cannot pass on any wrong information into the software. Almost all the commands are added into the menu bar. ‘Tab’ sequences and shortcut keys are also assigned to all the commands. Corresponding help files and a demo are also provided for the convenience of the user.

The present research work deals with various Industrial Engineering (IE) related multi-criteria decision-making problems where it is assumed that all the considered criteria, sub-criteria and alternative decision options are independent in nature. But in many practical situations, this assumption is violated. In these circumstances, a new and promising technique, like the analytic network process (ANP) can be incorporated in the decision-making process to take into account the dependencies amongst various criteria, sub-criteria and alternatives. In the usual decision-making problems, the judgments provided by the decision-makers are considered to be distinct and deterministic in nature. Here, the concepts, like fuzzy set theory and group decision-making approach can be used to give the present research work a more practical dimension. Other mathematical programming techniques, like goal programming and 0-1 integer programming methods, expert system (ES) and quality function deployment (QFD) can also be incorporated to validate the results provided by the analytic hierarchy process. Other Industrial Engineering related multi-criteria decision-making problems, like selection of the optimal forecasting technique, selection of optimal production schedule, selection of the best transportation route etc. can also be considered where the analytic hierarchy process (AHP) technique can be successfully implemented.