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An analytic network process-based approach to concept evaluation in a new product development environment

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Selecting the best product concept is one of the most critical tasks in a new product development (NPD) environment. Making decisions at this stage becomes very difficult due to imprecise and uncertain product requirements. So, the evaluation process of determining the most satisfying conceptual design has been a very vital issue for companies to survive in fast-growing markets for a long time. Therefore, most companies have used various methods to successfully carry out this difficult and time-consuming process. Of these methods, an analytic hierarchy process (AHP) has been widely used in multiple-criteria decision-making problems (*i.e.* concept selection, equipment evaluation). In this study, however, we use an analytic network process (ANP), a more general form of AHP, due to the fact that AHP cannot accommodate the variety of interactions, dependencies and feedback between higher and lower level elements. Briefly, in this paper, an ANP-based approach is presented to evaluate a set of conceptual design alternatives in order to reach to the best concept satisfying the needs and expectations of both customers and company. In addition, a numerical example is presented to illustrate the proposed approach.

Keywords: New product development; Concept selection; Multiple-criteria decision-making; Analytic network process

1. Introduction

Today's world is characterized by major changes in market and economic conditions, coupled with rapid advances in technologies. As the natural result of this, companies have been forced to develop new products for current markets, most of all technology-driven or high-tech markets. The changing economic conditions and technologies, combined with increased domestic and global competition, changing customer needs, rapid product obsolescence and the emergence of new markets, require very fast innovation process. The innovation process can be divided into three main areas: the fuzzy front end or project planning, the new product development (NPD) process, and commercialization.

An NPD process is the sequence of steps or activities that an enterprise employs to conceive, design and commercialize a product. Many of these steps and activities are intellectual and

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organizational rather than physical. One way to think about the development process is as the initial creation of a wide set of alternative product concepts and then the subsequent narrowing of alternatives and increasing specification of a product until the product can be reliably and repeatability produced by the production system. The concept development process typically includes the following activities; (1) identifying customer needs, (2) establishing target specifications, (3) concept generation, (4) concept selection, (5) concept testing, (6) setting final specifications, (7) project planning, (8) economic analysis, (9) benchmarking of competitive products, (10) modelling, and (11) prototyping. Early in the development process the product development team identifies a set of customer needs. By using a variety of methods (*i.e.* Quality function deployment (QFD)), the team then generates alternative solution concepts in response to these needs (Ulrich and Eppinger 2000). The first stage of the design process identifies the requirements of the customers. From these customer requirements, a list of product specifications is developed. The specifications are a list of functions that the product must provide and is given in a solution-neutral form. Concept design is the next stage in the design process and involves establishing a conforming set of sub-systems. Each of these sub-systems can perform a sub-set of the functions given in the specifications and, when taken as a whole, the entire set can perform all the required functions. During concept design, a number of different sub-systems are generated to perform each sub-set of the specified functions. After these various concepts have been outlined, the best combination of harmoniously conforming sub-systems is selected in terms of highest performance and lowest cost. This process is called concept selection (Ayağ 2005b).

Concept selection is often the Rubicon in the design process. It is vital that the best initial concepts are selected, as they determine the direction of the design embodiment stage. It is often said in the literature that nearly 60–80% of the cost is committed at this stage (Duffy *et al.* 1993). After this stage has been passed, the design process will diverge towards a detailed solution. Concept selection is therefore a vital part in the design process. It is recognized that the ability to rapidly evaluate design ideas, throughout their development within the design process, is an essential element in the goal to increase design productivity. Given the need for companies to produce more and more innovative products in an increasingly competitive market place, it follows that designers have to consider an increased number of design options. The activity of judging between and selecting from a range of competing design options is referred to as evaluation. As the number of options to evaluate increases and the time available decreases, it is evident that human evaluators will require increasing assistance in maintaining objective evaluation throughout development process.

As one of the most commonly used techniques for solving multiple-criteria decision-making (MCDM) problems, the analytic hierarchy process (AHP) was first introduced by Saaty (1981). In an AHP, a hierarchy considers the distribution of a goal among the elements being compared, and judges which element has a greater influence on that goal. In reality, a holistic approach such as an analytic network process (ANP) is needed if all attributes and alternatives involved are connected in a network system that accepts various dependencies. Several decision problems cannot be hierarchically structured because they involve the interactions and dependencies in higher or lower level elements. Not only does the importance of the attributes determine the importance of the alternatives as in AHP, but the importance of alternatives themselves also influences the importance of the attributes.

The objective of this paper is to present an ANP-based approach to concept selection problem in order to reach to the best solution satisfying the needs and expectations of both customers and company. Furthermore, a case study previously realized by Ayağ (2005b) was re-evaluated here to prove this approach's applicability and validity in order to make the approach more understandable especially for the decision-makers (*i.e.* product, design and project engineer) who involve in concept selection process in a NPD environment.

2. Related research

An NPD environment is a strategic business activity by intent or by default (Whitney 1988). It is not only the critical linkage between a business organization and its market, but it is also fundamental to business success. Business organizations need to manage their product development activities strategically to gain competitive advantage in the market place. Firms that fail to manage their product development activities strategically are not only running their business from a position of disadvantage, but also risking their future (Fitzsimmons *et al.* 1991). The critical role of NPD in the survival and success of business organizations, and the need for managing it strategically is being recognized increasingly in both the academic literature (Finger and Dixon 1989a, 1989b, Brown and Eisenhardt 1995, Griffin and Hauser 1996, Krishnan and Ulrich 2001) and the practitioner literature (Gates 1999, Chesbrough and Teece 2002, Welch and Kerwin 2003).

In an NPD process, concept selection is an important activity because it strongly influences its upstream and downstream activities in an NPD environment. As the result of this, many methods have been introduced to concept selection. In the literature, five main types of concept selection methods (CSMs) are defined by King and Sivaloganathan (1999) as follows; utility CSMs, AHP CSMs, graphical CSMs, QFD matrices, and fuzzy logic CSMs. The evaluation of each method and their comparison on each other are now briefly summarized.

- *Utility theory.* Utility theory has formed the basis for the majority of CSMs in the literature. The method was first developed for economic decision-making and has since been incorporated into a number of systematic design models. The core principle in the theory is a mapping of how criteria will vary across the range of each criterion. This relationship is governed by a utility function.
- *Analytic hierarchy process.* The AHP was first developed by Saaty (1981) for decision-making, and Marsh *et al.* (1991) developed a more specific method directly for design decision-making. The Marsh AHP has three steps ordering the factors (*i.e.* attributes) of a decision such that the most important ones receive greatest weight.
- *Graphical CSMs.* Pugh (1991) gives a simple graphical technique that centres on a matrix with columns (showing concepts) and rows (giving decision criteria). Pugh's evaluation matrix is very simple and fast. However, no measure is given of the importance of each of the criteria and it does not allow for coupled decisions. Therefore, there is a danger that the final concept can be distorted. The simplicity of Pugh's evaluation matrix makes the method a good screening process against highly unfeasible concepts and can allow the designer to focus on the best concepts using a different CSM.
- *QFD matrices.* QFD is a graphical adaptation of utility theory with several additions to assist decision-making. The building block of the method is a matrix chart known as a 'House of Quality', and the columns follow the method of utility as given earlier in this paper. While the matrix follows utility theory in many ways, the interaction chart gives a measure of coupled decisions. However, no numerical method is given to this measure into the QFD calculation. Without a numerical method, this become complex for most design situations where many concepts are visual comparison would be almost impossible.
- *Fuzzy logic.* Fuzzy logic is a concept used when a decision needs to be made near the boundary of two outcomes. Thurston and Carnahan (1992) proposed the application of fuzzy set theory to multiple criteria engineering design evaluation process. They do not use normalized weights in order that the extended division will not be needed in the calculation. They developed a fuzzy logic CSM.
- *Evaluation of CSMs.* The aforementioned CSMs can be compared with each other as follows. At a conceptual design phase, if information quality may be low, and so systematic

> methods are the easiest to use, such as those of Pahl and Beitz (1984), Pugh charts (Pugh 1991) are appropriate. Most methods reviewed allow for multiple attributes to a decision, although the QFD matrix method represents this facility with greatest clarity because of its graphical template. The QFD method provides a qualitative interaction table, but this is used for 'optimal conflict information' and does not provide a quantitative analysis of how one decision affects another. A choice to use one technology or component will significantly affect the rest of the design. The fuzzy logic method does require a rather lengthy methodology and is by no means easy to use. It is still necessary to determine the mathematical equation in order to establish a solution. In the field of design decision-making, many decisions are not based upon known (or definable) mathematical equations. The methodology therefore has a very limited advantage when considered as a general methodology for a CSM. In addition, none of the utility methods given in the literature accommodate coupled decisions within the calculation, although they are a reality in most design situations.

As one of the aforementioned CSMs, AHP has been widely used for MCDM selection problems in the literature (for example, Zahedi 1986, Ayağ 2002, 2005a, Scott 2002) since it was first introduced by Saaty (1981). In this study, we used an ANP, a more general form of an AHP due to the fact that the AHP cannot accommodate the variety of interactions, dependencies and feedback between higher and lower level elements. In other words, an ANP incorporates feedback and interdependent relationships among decision attributes and alternatives (Saaty 1996). This provides a more accurate approach for modelling a complex decision environment (Meade and Sarkis 1999, Lee and Kim 2000, Agarwal and Shankar 2003, Yurdakul 2003).

The ANP method is now briefly described. Although the AHP is the more commonly used method in solving various MCDM problems, in some cases problems cannot be always hierarchically structured in practice because there are possible relationships or interactions and dependencies between the higher-level elements and lower-level elements. Therefore, what is needed is to develop a holistic model that can directly accommodate complicated decision-making problems without decomposing them into a simple form. The ANP may be applied to fulfil such complex requirements. The ANP approach may be considered as a second-generation AHP, which has been designed to overcome more complex problems. It replaces hierarchies with network systems that permit all possible elements and join them together in network structures. With its strength, the modelling of the interactions and dependencies among elements of the problem, an ANP may be applied to generate a better in-depth analysis and to deliver a more accurate result than an AHP.

In the literature, to the best of our knowledge, a number of studies have been realized in various fields using the ANP since it first was introduced by Saaty (1996). Some of them are presented here. Hamalainen and Seppalainen (1986) presented an ANP-based framework for a nuclear power plant licensing problem in Finland. They used the pair-wise comparison process with the consistency index to determine the weightings of the alternatives. The ANP is also used to incorporate product lifecycle into replacement decisions. The multi-attribute, multi-period model handles vital dynamic factors as well as interdependence among system attributes. The system attributes' relative importance that varies during the different stages of product lifecycle is captured in this model (Azhar and Leung 1993). Meade and Presley (2002) used the ANP method for R&D project selection. Agarwal and Shankar (2003) presented a framework for selecting the trust-building environment in an e-enabled supply chain. Lee and Kim (2000) proposed an integration model by integrating the ANP and goal programming for interdependent information system project selection. Yurdakul (2003) used the ANP method to measure long-term performance of a manufacturing company.

In addition, some design-related works have been done in the literature; a few of them are presented as follows. Thurston and Carnahan (1992) used fuzzy ratings and utility analysis in preliminary design evaluation of multiple attributes. Carnahan *et al.* (1994) also used fuzzy ratings for multi-attribute decision-making. Buyukozkan *et al.* (2004) used a fuzzy ANP to prioritize design requirements by taking into account the degree of the interdependence between the customer needs and design requirements and the inner dependence among them. Mikhailov and Singh (2003) used a fuzzy ANP and its application to the development of decision support systems.

In the following section, we propose an ANP-based approach to evaluate a set of conceptual design alternatives in order to find out the best concept satisfying the needs and expectations of both customers and company. We also defined an ANP-based framework that identifies critical determinants, dimensions and attribute-enablers used in concept selection.

3. An ANP-based approach

The schematic representation of the ANP-based framework and its decision environment related to concept selection is shown in the following section on the case study (figure 1). The overall objective is to determine the best conceptual design. The elements (*i.e.* determinants, dimensions and attribute-enablers) used for evaluating a set of conceptual design alternatives are determined based on the needs and expectations of both customers and company. Although some of these elements may differ from one company to another or from one product to another, those used in a typical concept evaluation process is presented in figure 1. These elements are very critical at the stage of concept evaluation in a NPD environment, and should be

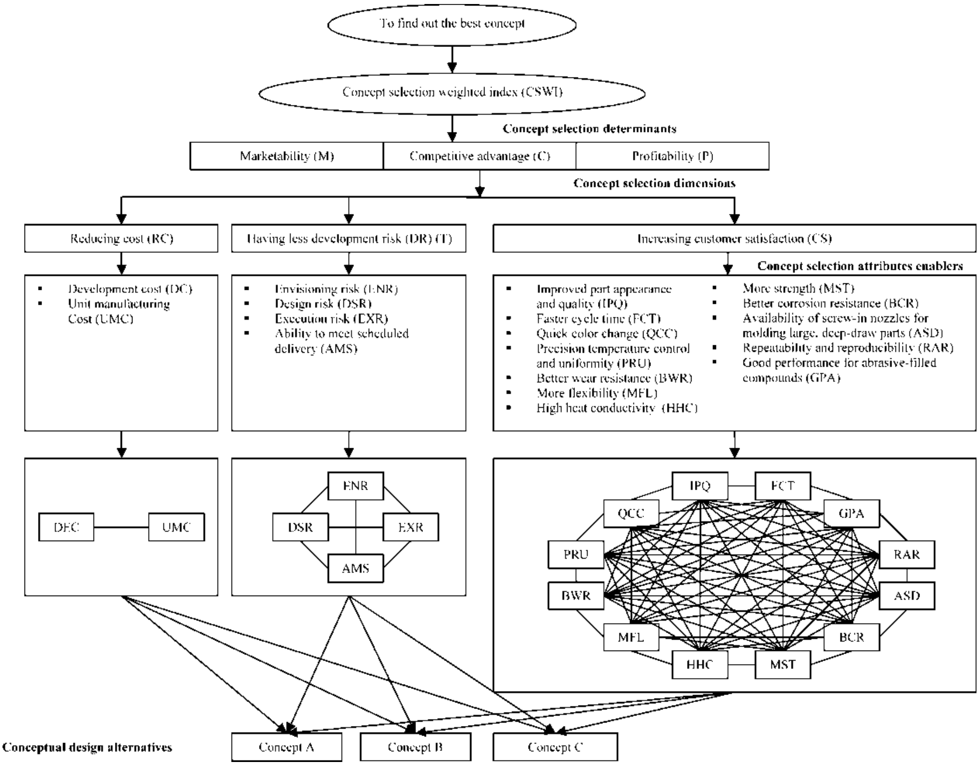

Figure 1. The ANP-based framework for concept selection.

Table 1. Nine-point fundamental scale used in pair-wise comparisons (Saaty 1989).

Numerical rating	Judgment or preference	Remarks
1	Equally important	Two attributes contribute equally to the attribute at the higher decision level
3	Moderately more important	Experience and judgement slightly favour one attribute over another
5	Strongly more important	Experience and judgement strongly favour one attribute over another
7	Very strongly more important	Experience and judgement strongly favour one attribute over another; its dominance has been demonstrated in practice
9	Extremely more important	Experience and judgement extremely favour one attribute over another; the evidence favouring one attribute over another is of the highest possible order of affirmation

well-defined due to the fact that they play an important role in finding out the best conceptual design out of the available options.

For representation of pair-wise comparison, firstly, the hierarchy of concept selection should be established. The ANP method represents relationships hierarchically but does not require as strict a hierarchical structure, and therefore allows for more complex interrelationships among the decision levels and attributes. After constructing flexible hierarchy, the decision-maker(s) (product and/or design engineer in the product engineering department of a company) is(are) asked to compare the elements at a given level on a pair-wise basis to estimate their relative importance in relation to the element at the immediate proceeding level. In a conventional ANP, the pair-wise comparison is made using a ratio scale. A frequently used scale is the nine-point scale developed by Saaty (1989) that shows the participants judgements or preferences. Table 1 presents this fundamental nine-point scale.

To obtain an understanding of the ANP methodology for concept selection, the seven steps are presented as follows.

3.1 *Step I: model construction and problem structuring*

The top-most elements in the hierarchy of determinants are decomposed into dimensions and attribute-enablers. The decision model development requires identification of dimensions and attribute-enablers at each level and the definition of their interrelationships. The ultimate objective of hierarchy is to identify alternatives that are significant for determining the best conceptual design. In this study, we determined three evaluation determinants (marketability, competitive advantage and profitability) that are aggregated in the final concept selection weighted index (CSWI) selection step. To define this hierarchy, we also utilized Saaty's suggestions of using a network for categories of benefits, costs, risks and opportunities (Saaty 1996). Instead of Saaty's categories, we used evaluation determinants, which are very important in concept selection. In order to analyse the combined influence of three determinants on concept selection, a CSWI is calculated to prioritize conceptual design alternatives. This index also takes the influences of dimensions and attribute-enablers into consideration.

3.2 *Step II: building pair-wise comparison matrices between component/attributes levels*

By using the nine-point scale of Saaty (table 1), the decision-maker(s) are asked to respond to a series of pair-wise comparisons with respect to an upper-level 'control' criterion. These are conducted with respect to their relevance importance towards the control criterion. In the case of interdependencies, components in the same level are viewed as controlling components for each other. Levels may also be interdependent. The nine-point scale is used to compare two components, with a score of 1 representing differences between two components and 9 being an overwhelming dominance of the component under consideration over the comparison component. When scoring is conducted for a pair, a reciprocal value is automatically assigned to the reverse comparison within the matrix. That is, if a_{ij} is a matrix value assigned to the relationship of component i to component j, then a_{ij} is equal to $1/a_{ij}$ or $a_{ij} = 1$. Once the pair-wise comparisons are completed, the local priority vector w (also referred to as the e-vector) is computed as the unique solution to;

$$Aw = \lambda_{\max} w \tag{1}$$

where $\lambda_{\max}$ is the largest eigenvalue of A.

Saaty defines several algorithms for approximating w. In this study, we used a two-stage algorithm that involves forming a new $n \times n$ matrix by dividing each element in a column by the sum of the column elements, and then summing the elements in each row of the resultant matrix and dividing them by the n elements in the row. This is referred to as the process of averaging over normalized columns. This represented as follows:

$$w_i = \frac{\sum_{i=1}^{I} \left(\frac{a_{ij}}{\sum_{j=1}^{J} a_{ij}} \right)}{J} \tag{2}$$

where w_i is the weighted priority for component i, J is the index number of columns or components, and I is the index number of rows or components.

3.3 *Step III: checking out consistency ratios for pair-wise comparison matrices*

After constructing all pair-wise matrices between component/attributes levels, the consistency ratio (CR) should be calculated for each of them. The deviations from consistency are calculated using equation (3); the measure of inconsistency is called the consistency index (CI):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

The CR is used to estimate directly the consistency of pair-wise comparisons. The CR is computed by dividing the CI by a value obtained from a table of Random Consistency Index (RI), the average index for randomly generated weights (Saaty 1981):

$$CR = \frac{CI}{RI} \tag{4}$$

If the *CR* is less than 10%, the comparisons are acceptable; otherwise they are not.

3.4 *Step IV: pair-wise comparison matrices of inter-dependencies*

In order to reflect the interdependencies in a network, pair-wise comparisons among all the attribute-enablers are constructed and their consistency ratios calculated as previously defined in sections 2.3 and 2.3.

3.5 *Step V: super-matrix formation and analysis*

The super-matrix formation allows a resolution of the effects of interdependence that exists between the elements of the system. The super-matrix is a partitioned matrix, where each sub-matrix is composed of a set of relationships between two levels in the graphical model. Three types of relationships may be encountered in this model: (1) independence from succeeding components, (2) interdependence among components, and (3) interdependence between levels of components. Raising the super-matrix to the power $2k + 1$, where k is an arbitrary large number, allows convergence of the interdependent relationships between the two levels being compared. The super-matrix is converged to obtain a long-term stable set of weights.

3.6 *Step VI: selection of the best concept alternative*

The equation of *desirability index*, D_{ia} for concept alternative i and determinant a is defined as follows:

$$D_{ia} = \sum_{j=1}^{J} \sum_{k=1}^{K_{ja}} P_{ja} A^{D}_{kja} A^{I}_{kja} S_{ikja} \tag{5}$$

where P_{ja} is the relative importance weight of dimension j on determinant a, A^{D}_{kja} is the relative importance weight for attribute-enabler k of dimension j, and determinant a for the dependency (D) relationships between attribute-enabler's component levels, A^{I}_{kja} is the stabilized relative importance weight for attribute-enabler k of dimension j, and determinant a for the independency (I) relationships within an attribute-enabler's component level, S_{ikja} is the relative impact of concept alternative i on attribute-enabler k of dimension j of the concept selection network, K_{ja} is the index set of attribute-enablers for dimension j of determinant a, and J is the index set for attribute j.

3.7 *Step VII: calculation of the concept selection weighted index*

To finalize the analysis of concept selection, the CSWI is calculated for each alternative. The CSWI$_i$ for an alternative i is the product of the desirability indices, D_{ia}. After calculating CSWI values for each concept alternative, they are normalized to prioritize the alternatives to determine the one with highest value.

4. Case study

An ANP-based approach has been presented to evaluate a set of conceptual design alternatives in an NPD environment. In this section, a case study is presented to prove this approach's applicability and validity on a real-life example. This case study was realized at the product engineering department of a hot runner system manufacturer in Ontario, Canada. This company, with ISO 9000 certification, designs and manufactures all kinds of standard, semi-custom and custom hot runner systems for the world market. A hot runner system is integral part of a mould that can contain sizeable quantity of melted plastics in relation to the part(s). In other words, it is critical component in the hot halve part of an injection mould and is used to transfer a certain amount of melted plastics material to the cavity (or cavities) by keeping its temperature along the way. This company designs and manufactures three groups of hot runner systems that can be generally classified into standard (N), semi-custom (S)—the products designed and manufactured using similar standard products—and custom (P), the products completely designed from sketch and manufactured first time.

Due to the tight competitive conditions in the market, the company's top management decided to develop a new kind of hot runner manifold and horizontal hot tip nozzle system (S-type) especially for the fast-growing automotive industry, in order to keep their competitive advantage in the following years. The new system would be made of stainless steel, as in existing products. Then, a cross-functional project team consisting of various departments in the company worked for 4 months to create a set of conceptual design alternatives, and suggested three different concepts, named concept A, concept B and concept C, respectively.

To generate the concepts, the team operated as follows: (1) define the problem—general understanding of a new hot runner system design for the automotive industry; (2) external sources—interview with lead mould-makers, consult suppliers for each critical system component, literature on technical documents (*i.e.* mould-making, hot runner system design) to find out existing solutions and more, benchmarking study of competitor products and patents for mould and hot runner system design; (3) internal sources—the use of personal and team knowledge and creativity; (4) organization of the possible set of the concepts using a classification tree that divides the entire space of possible solutions into distinct classes, which facilitates comparison and pruning; and (5) final evaluation (the first four steps were evaluated again to make sure that the entire space of concepts are fully explored).

The determinants, dimensions and attribute-enablers used in the ANP framework are presented table 2, while in they are illustrated in graphic form in figure 1.

Reducing cost only includes the development cost and unit manufacturing cost of a product. *Having less development risk* can be categorized as follows: (1) *envisioning risk*—will a product with the targeted product attributes of the product vision create value for the customer and the company?; (2) *design risk*—does the product design embody the targeted product attributes of the product vision?; (3) *execution risk*—can the development team execute the

Table 2. Determinants/dimensions/attribute-enablers used in the ANP framework.

Element	Code	Definition
Determinants	M	Marketability
	C	Competitive advantage
	P	Profitability
Dimensions	RC	Reducing cost
	DR	Having less development risk
	CS	Increasing customer satisfaction
Attribute-enablers	DEC	Development cost
	UMC	Unit manufacturing cost
	ENR	Envisioning risk
	DSR	Design risk
	EXR	Execution risk
	AMS	Ability to meet scheduled delivery
	IPQ	Improved part appearance and quality
	FCT	Faster cycle time
	QCC	Quick colour change
	PRU	Precision temperature control and uniformity
	BWR	Better wear resistance
	MFL	More flexibility (*i.e.* gating options, various nozzle sizes)
	HHC	High heat conductivity
	MST	More strength
	BCR	Better corrosion resistance
	ASD	Availability of screw-in nozzles for moulding large, deep-draw parts
	RAR	Repeatability and reproducibility
	GPA	Good performance for abrasive-filled compounds

conversion of the product design into a delivered product?; and (4) *ability to meet scheduled delivery*—especially, the hot runner systems are used for mould-makers, which have tight due dates of their injection moulds for automotive industry. Delivering on time is quite critical. *Increasing customer satisfaction* or product performance on plastic products for automotive industry for customers (*i.e.* mould-makers) is involved in the product specifications (*i.e.* improved part appearance and quality, faster cycle time, etc.) defined by the mould-makers.

In this paper, three determinants (*i.e.* marketability, competitive advantage and profitability) with network relationships with each other were defined. For example, higher profitability results in increasing competitive advantage of company. On the other hand, if marketability of product increases, then profitability gets higher. For each type of determinant, we also defined the following dimensions and network relationships with each other: reducing cost, having less development risk and increasing customer satisfaction. For example, while reducing cost increases the development risk, on the other hand it might increase the profitability and customer satisfaction. In addition, we defined attribute-enablers for each dimension under each determinant with their network relationships. For example, a faster cycle time results in better customer satisfaction, reducing cost and high profitability.

Then, in order to determine the best concept, we carried out the ANP-based approach using the nine-point scale of Saaty (table 1) to express the preference in the pair-wise comparisons. First, we obtained the pair-wise comparison matrix for the relative importance of the determinants. Then, we calculated eigenvalue of the matrix A by solving the characteristic equation of A, $\det(A - \lambda I) = 0$, and found all λ values for $A(\lambda_1, \lambda_2, \lambda_3)$. The largest eigenvalue of pair-wise matrix, $\lambda_{\max}$, was calculated using equations (1) and (2). The dimension of the matrix, n, is 3 and the random index, $RI(n)$, is 0.58 (RI—function of the number of attributes; Saaty 1981). Finally, we also calculated the CI and the CR of the matrix using equations (3) and (4). Because the CR was less than 0.10, the pair-wise comparison was acceptable. Table 3 shows the pair-wise comparison matrix for the relative importance of the determinants.

By following the same method, three pair-wise comparison matrices for the relative importance of the dimensions (RC, DR, and CS) for the determinants (M, C and P) were constructed and their consistencies checked out, which were less than 0.10 and acceptable. Table 4 shows only the pair-wise comparison matrix for the relative importance of the dimensions for the determinant *marketability* (M).

In addition, nine pair-wise comparison matrices for the relative importance of the attribute-enablers for the dimensions (RC, DR and CS) and the determinants (M, C and P) were constructed and their consistencies checked out, which were less than 0.10 and acceptable. Table 5 shows only a pair-wise comparison matrix for the relative importance of the attribute-enablers for the dimension *reducing cost* (RC) and the determinant *marketability* (M).

Then, 54 pair-wise comparison matrices for the relative importance of concept alternatives (A, B and C) for each attribute-enabler of the dimensions for three determinants were

Table 3. Pair-wise comparison matrix for the relative importance of the determinants (CR = 0.056).

Determinant	M	C	P	e-vector
M	1	3	7	0.643
C	1/3	1	5	0.283
P	1/7	1/5	1	0.074
			$\lambda_{\max}$	3.066
			CI	0.033
			RI	0.58
			CR	0.056 < 0.100 (OK)

Table 4. Pair-wise comparison matrix for the relative importance of the dimensions for *marketability* (M) (CR = 0.25).

Marketability (M)				
Dimension	RC	DR	CS	e-vector
RC	1	5	9	0.748
DR	1/5	1	3	0.180
CS	1/9	1/3	1	0.071
			λ_{max}	3.029
			CI	0.015
			RI	0.58
			CR	$0.025 < 0.100$ (OK)

Table 5. Pair-wise comparison matrix for the relative importance of the attribute-enablers of *reducing cost* (RC) for *marketability* (M).

Marketability (M)			
Reducing cost (RC)	DC	UMC	e-vector
DC	1	5	0.833
UMC	1/5	1	0.167

constructed and their consistencies checked out, which were less than 0.10 and acceptable. Table 6 shows the pair-wise comparison matrix of concept alternatives for the attribute-enabler *development cost* (DC) of the dimension *reducing cost* (RC) for the determinant *marketability* (M).

To reflect the inter-dependencies in network, we then also built pair-wise comparison matrices for each of the attribute-enablers for three determinants of concept selection clusters. A total of 54 matrices were built. Table 7 presents the pair-wise comparison matrix of the attribute-enablers under *marketability* (M), *reducing cost* (RC) and *development cost* (DC).

Similarly, pair-wise comparison matrices for other attribute-enablers were constructed as shown in table 7, and all resultant e-vectors are presented in table 8 to build the super-matrix.

Table 6. Pair-wise comparison matrix for the relative importance of concept alternatives under *marketability* (M), *reducing cost* (RC) and *development cost* (DC) (CR = 0.01).

Marketability (M)				
Development cost (DC)	Concept A	Concept B	Concept C	e-vector
Concept A	1	1	5	0.435
Concept B	1	1	9	0.487
Concept C	1/5	1/9	1	0.078
			λ_{max}	3.013
			CI	0.006
			RI	0.58
			CR	$0.01 < 0.10$ (OK)

Table 7. Pair-wise comparison matrix for the relative importance of the attribute-enablers under *marketability* (M), *reducing cost* (RC) and *development cost* (DC).

Development cost (DC)	UMC	e-vector
UMC	1	1

Table 8. Super-matrix for *marketability* (M) before convergence.

M	DEC	UMC	ENR	DSR	EXR	AMS	IPQ	FCT	QCC	PRU	BWR	MFL	HHC	MST	BCR	ASD	RAR	GPA
DEC	0.000	1.000																
UMC	1.000	0.000																
ENR			0.000	0.685	0.655	0.600												
DSR			0.669	0.000	0.187	0.200												
EXR			0.243	0.179	0.000	0.200												
AMS			0.088	0.136	0.158	0.000												
IPQ							0.000	0.272	0.272	0.242	0.243	0.241	0.308	0.282	0.298	0.323	0.288	0.291
FCT							0.247	0.000	0.151	0.192	0.192	0.193	0.202	0.210	0.228	0.204	0.251	0.254
QCC							0.227	0.189	0.000	0.188	0.185	0.183	0.122	0.123	0.120	0.127	0.115	0.109
PRU							0.132	0.145	0.143	0.000	0.091	0.090	0.081	0.077	0.078	0.075	0.081	0.084
BWR							0.093	0.093	0.103	0.086	0.000	0.074	0.072	0.091	0.070	0.065	0.053	0.041
MFL							0.077	0.077	0.089	0.069	0.063	0.000	0.031	0.036	0.039	0.040	0.036	0.044
HHC							0.045	0.048	0.061	0.048	0.050	0.042	0.000	0.045	0.044	0.043	0.048	0.042
MST							0.035	0.035	0.033	0.035	0.037	0.039	0.026	0.000	0.030	0.028	0.038	0.039
BCR							0.028	0.028	0.029	0.026	0.027	0.027	0.033	0.026	0.000	0.032	0.029	0.032
ASD							0.036	0.036	0.038	0.036	0.034	0.034	0.033	0.034	0.032	0.000	0.030	0.030
RAR							0.034	0.034	0.036	0.033	0.034	0.033	0.045	0.032	0.029	0.029	0.000	0.034
GPA							0.045	0.044	0.045	0.044	0.044	0.044	0.026	0.043	0.032	0.032	0.031	0.000

Table 9. Super-matrix for *marketability* (M) after convergence (A^{25}).

M	DEC	UMC	ENR	DSR	EXR	AMS	IPQ	FCT	QCC	PRU	BWR	MFL	HHC	MST	BCR	ASD	RAR	GPA
DEC	0.000	1.000																
UMC	1.000	0.000																
ENR			0.398	0.398	0.398	0.398												
DSR			0.320	0.320	0.320	0.320												
EXR			0.175	0.175	0.175	0.175												
AMS			0.106	0.106	0.106	0.106												
IPQ							0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207
FCT							0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
QCC							0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148
PRU							0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
BWR							0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077
MFL							0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
HHC							0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
MST							0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
BCR							0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
ASD							0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
RAR							0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
GPA							0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039

Table 10. Concept selection desirability index for *marketability* (M) ($a = 1$).

Dimension	Attribute-enabler	P_{j1}	A_{kj1}^{D}	A_{kj1}^{I}	S_{1kj1}	S_{2kj1}	S_{3kj1}	Concept alternatives		
								Concept A	Concept B	Concept C
RC	DEC	0.748	0.833	1.000	0.435	0.487	0.078	0.27104	0.30344	0.04860
	UMC	0.748	0.167	0.000	0.429	0.429	0.142	0.00000	0.00000	0.00000
DR	ENR	0.180	0.511	0.398	0.480	0.405	0.115	0.01757	0.01483	0.00421
	DSR	0.180	0.159	0.320	0.633	0.260	0.107	0.00580	0.00238	0.00098
	EXR	0.180	0.059	0.175	0.333	0.333	0.334	0.00062	0.00062	0.00062
	AMS	0.180	0.071	0.106	0.120	0.746	0.134	0.00016	0.00101	0.00018
CS	IPQ	0.071	0.232	0.207	0.136	0.685	0.179	0.00046	0.00234	0.00061
	FCT	0.071	0.214	0.167	0.143	0.143	0.714	0.00036	0.00036	0.00181
	QCC	0.071	0.129	0.148	0.158	0.187	0.655	0.00021	0.00025	0.00089
	PRU	0.071	0.091	0.102	0.136	0.179	0.685	0.00009	0.00012	0.00045
	BWR	0.071	0.080	0.077	0.490	0.451	0.059	0.00021	0.00020	0.00003
	MFL	0.071	0.048	0.062	0.480	0.405	0.115	0.00010	0.00009	0.00002
	HHC	0.071	0.034	0.045	0.435	0.487	0.078	0.00005	0.00005	0.00001
	MST	0.071	0.035	0.032	0.405	0.115	0.480	0.00003	0.00001	0.00004
	BCR	0.071	0.034	0.027	0.143	0.143	0.714	0.00001	0.00001	0.00005
	ASD	0.071	0.031	0.033	0.333	0.333	0.334	0.00002	0.00002	0.00002
	RAR	0.071	0.041	0.032	0.633	0.260	0.107	0.00006	0.00002	0.00001
	GPA	0.071	0.031	0.039	0.120	0.746	0.134	0.00001	0.00006	0.00001
Total desirability indices (D_{i1}) of *marketability* (M) for concept alternatives								0.297	0.326	0.059

The final standard pair-wise comparison evaluations are required for the relative impacts of each concept alternative for concept selection. The number of pair-wise comparison matrices is dependent of the number of the dimensions and the attribute-enablers that are included in the determinant of concept selection hierarchy. In this case study, we constructed 94 pair-wise comparison matrices at all levels of relationships in the concept selection hierarchy.

Table 8 presents the super-matrix, M, detailing results of the relative importance measures for each of the attribute-enablers for the determinant *marketability* of concept selection clusters. Since there are 18 pair-wise comparison matrices, one for each of the interdependent attribute-enablers in the *marketability* hierarchy, there will be 18 non-zero columns in this super-matrix. Each of non-zero values in the column in super-matrix, M, is the relative importance weight associated with the interdependent pair-wise comparison matrices. In this study, there are three super-matrices, one for each of the determinants (M, C and P) of the best concept selection hierarchy network. Then, all the super-matrices were converged to obtain a long-term stable set of weights. For this the power of the super-matrix was raised to an arbitrarily large number. In our case study, convergence for the super-matrix constructed under the determinant *marketability* (M) was reached at the 25th power. Table 9 shows the values of the super-matrix after convergence.

To determine the best concept alternative, we used equation (5) and made the calculations for the desirability indices (D_{ia}, where $a = 1$ for the determinant *marketability*) for concept alternatives based upon the determinant *marketability* control hierarchy using the weights obtained from the pair-wise comparisons of concept alternatives, dimensions and attribute-enablers from the converged super-matrix. The weights were used to calculate a score for the determinant *marketability* of concept selection desirability for each concept alternative being considered. For example, the desirability indices of concept A, concept B and concept C under the first determinant *marketability* (M), where index $a = 1$, was calculated respectively using equation (5) as illustrated in table 10.

Finally, to reach the best concept, we calculated the CSWI for each concept alternative (A, B and C). The final results are presented in table 11. As can easily be seen in table 11, the best concept alternative among the S-type hot runner manifold and horizontal hot tip nozzle system alternatives is concept A.

After the team determined that the best concept is concept A, they carried out the following steps to translate the chosen concept using the necessary information (*i.e.* bill-of-materials information, process plan, assembly chart, etc.) to reality: (1) estimate the manufacturing costs (*i.e.* component costs, assembly costs and overhead costs), (2) reduce the costs of components (understanding the process constraints and cost drivers, redesigning components to eliminating processing steps, choosing the appropriate economic scale for the part process, standardizing components and processes), (3) reduce the costs of assembly (keeping score, integrate parts and maximize ease of assembly), (4) reduce the costs of production-related activities, (5) design and organize the necessary hardware (*i.e.* machines, fixtures and tools) for some components

Table 11. CSWI for concept alternatives.

	Determinants		Calculated weights for alternatives		
Concept alternatives	*Marketability* (M), 0.643	*Competitive advantage* (C), 0.283	*Profitability* (P), 0.074	CSWI	Normalization
Concept A*	0.297	0.174	0.165	0.252	0.469
Concept B	0.326	0.041	0.088	0.227	0.423
Concept C	0.059	0.052	0.073	0.058	0.108
Total				0.537	1.000

*The most preferred concept alternative.

of the new system, (6) make a ramp-up or pilot manufacturing, and (7) schedule a serial production. Then they introduced the new system to the world markets in a limited number in order to firstly see its performance. After a couple of months, a customer survey showed that the new system perfectly met the needs and expectations of both customers and company. It is now a very competitive product in the world market.

5. Conclusions

The objective of the research was to use an ANP-based approach to evaluate a set of conceptual design alternatives in an NPD environment in order to reach to ultimate conceptual alternative that satisfies the needs and expectations of both customers and company.

Comparison of the methods with the ANP is given as follows. At a conceptual design phase, if information quality may be low and so systematic methods are the easiest to use, such as those of Pahl and Beitz (1984), Pugh charts (Pugh 1991) are appropriate. Pugh's evaluation matrix is very simple and fast. However, no measure is given of the importance of each of the criteria and it does not allow for coupled decisions. Therefore, there is a danger that the final concept can be distorted. The QFD matrix follows utility theory in many ways; the interaction chart gives a measure of coupled decisions. However, no numerical method is given to this measure in the QFD calculation. Without a numerical method, this becomes complex for most design situations where for many concepts visual comparison would be almost impossible. The fuzzy logic method does require a rather lengthy methodology and is by no means easy to use. It is still necessary to determine the mathematical equation in order to establish a solution. In the field of design decision-making, many decisions are not based upon known (or definable) mathematical equations. The methodology therefore has a very limited advantage when considered as a general methodology for a CSM. In addition, none of the utility methods given in the literature accommodate coupled decisions within the calculation, although they are a reality in most design situations.

The ANP methodology developed by Saaty (1996) is quite new and vastly improved over the AHP method as it allows for feedback between the hierarchical levels. The ANP methodology also lends itself to quantitative as well as qualitative analysis; most decision-makers are interested in both types of analyses. It is also a robust MCDM technique for synthesizing the elements (*i.e.* determinants, dimensions and attribute-enablers) governing the finding of the best alternative. It integrates these elements in a decision model to capture their relationships and interdependencies across and along the hierarchies. It is also effective as both quantitative and qualitative characteristics can be considered simultaneously without sacrificing their relationships. The back-end and front-end of product development mainly affects defining determinants, dimensions and attribute-enablers used in the ANP method. The ANP needs well-defined elements in a decision network, which are obtained from customer expectations, technical specifications and more information created during a development project in an NPD environment.

As compared with the AHP, the analysis using the ANP is relatively cumbersome because a great deal of pair-wise comparison matrices should be constructed for a typical study. In our study, we built 121 matrices. Acquiring the relationships among determinants, dimensions and attribute-enablers required very long and exhaustive effort. On the other hand, an advantage of the ANP method is to capture interdependencies across and along the decision hierarchies. This means that the ANP provides a more reliable solution than the AHP. The full support of management in the ANP will help use their long experience and thus eliminate the biases in the weights for conceptual design alternatives. Although the AHP is easier to apply than the ANP, in this study we selected the ANP—both due to the fact that its holistic view and interdependencies accounted in the ANP, and due to the fact that it generates more reliable solution than the AHP. Making wrong decisions in selecting the best concept can put a company into undesired risk in terms of losing the market share, cost and time.

This approach also can be easily used by a product or/and design engineer, as part of a cross-functional team in a company. For motivation of the team and its members, and the success of a study, the support of the top management of company, especially from the departments of product development, quality and manufacturing, should be provided.

For future study, due to the vagueness and uncertainty on judgements of the decision-maker(s), the nine-point-scale pair-wise comparison in the conventional ANP could be insufficient and imprecise to capture the right judgements of decision-maker(s). Therefore, fuzzy logic can be integrated to this approach in a good manner.

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