The Third International Conference on Design Creativity (3rd ICDC)
ISBN 978-1-904670-60-5
Bangalore, India, 12th-14th January 2015

UNCERTAINTY AND DECISION MAKING IN PRODUCT DESIGN: A FUZZY APPROACH

P. Kumar[1] and P. Tandon[1]

[1] Mecanical Department, PDPM IIITDM, Jabalpur, India

Abstract: Design of any product is associated with a number of elements like technical parameters, material properties, functional and geometrical interdependence, etc. A balance between the technical parameters and creativity is necessary for a successful product design. To address this, a mathematical model is generally proposed, which many times, may not be a correct representation. For mathematical models, the tendencies and relationships remain true for a specified period of time only. The applications of fuzzy for the design decision deliver accurate information related to customer needs. In this paper, a design method for the reservoir of an air cooler is proposed to handle uncertainty using fuzzy logic. This method helps develop a dedicated tool for handling uncertainty and allows to take advantage of the creativity-based design process to achieve the goals of innovative product design.

Keywords: design decission, uncertainty, fuzzy logic

1. Introduction

Product design is a process of creating new products to fulfil the customer requirements. One of the important objectives of the product design is to meet conflicting objectives under an uncertain environment. Design is not only uncertain process, but due to uncertainty it may also lead to multisolutions, which itself is a problem. However, traditionally the ultimate decision is made based on the designer's individual talent and subjective knowledge. According to Pahl et al., (2007) the right idea rarely comes at the right moment. For design decisions, many times, a mathematical model is used. This model may not be a correct or valid representation every time as the variables might change with time or may be, due to change in any technical parameter. Hence, developing a systematic approach to evaluate the uncertainty to obtain a well-designed product decision is necessary. In this work, a fuzzy decision-making approach for making design decisions and space for creativity under uncertainty is proposed. Fuzzy logic is a rule-based decision process. Now a days, application of fuzzy logic for creating decision-support has grown. A number of approaches, methods, and models have been proposed for the design under uncertainty which embrace different scope, such as, fuzzy product line design (Lin et al., 2011) stochastic nonlinear systems (Li et al., 2014), quality function deployment (Chen & Ko 2009), new product development portfolio management (Oh & Lee 2012), production planning, etc. On exploring the literature on uncertainty, fuzzy logic is the most popular tool to not only address it but also for pattern recognition, economics, data analysis, and other areas that involve a high level of uncertainty, complexity, or nonlinearity. In the proposed work, fuzzy rules that are based on the human knowledge are applied for design decisions under uncertainty in the form of IF-THEN statements. As the product design typically involves multiple objectives that are at times partly conflicting with each other (Li & Azarm 2000) fuzzy IF- THEN rule is applied for the same. Usually, experts provide their assessments by using just one linguistic term (Liu & Rodríguez 2014) which may be in the form of, for example, high, medium and low, or adequate / inadequate, or may be any similar expression. Fuzzy logic can be used to capture these linguistic terms in a quantitative manner and help in logical decision making.

The proposed method is validated by designing an evaporative cooler system of uncertain reservoir capacity with sufficient flexibility provided to the designer. An evaporative cooler is the oldest, simplest, cheap and efficient form of air conditioning. Figure 1 shows the schematic diagram of an evaporative cooler. Evaporative cooling works by employing water's large enthalpy of vaporization. In evaporative cooler a water pump circulates water from the reservoir (water tank) to cooling mat. A fan draws air from outside the surroundings through the moisturized pad. As the surrounding hot air passes through the moisturized pad the air is cooled by evaporation. Hence, the key to effective evaporative cooling depends on its design and cooling pads wetness level during operation.

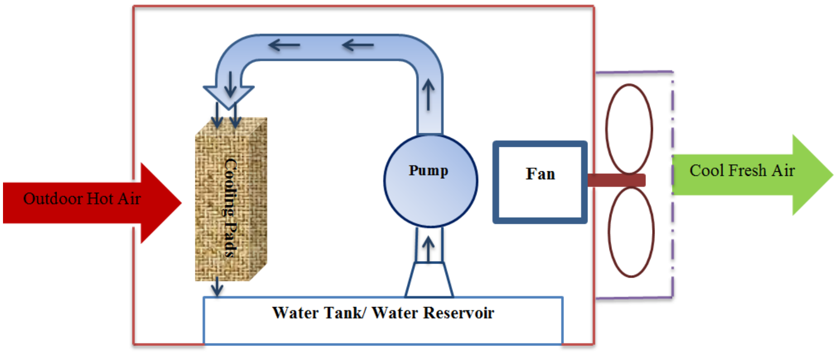

Figure 1. Schematic diagram of evaporative cooler

Evaporative cooler design depends on the technical parameters like cooling pad thickness, water reservoir size, blade size, fan speeds, horsepower, etc. Uncertainty with regard to design decisions for evaporative cooler reservoir is addressed with the help of fuzzy logic. Two technical parameters i.e. (a) nominal air capacity and (b) cooling capacity are considered to evaluate the optimal capacity of air cooler reservoir. In this work, uncertainty associated with the two design parameters is addressed by fuzzy IF-THEN rules and this in turn, facilitates design automation. The motivation behind using fuzzy IF-THEN rules is conceptually easy to understand and follows natural approach. With the help of fuzzy logic we can model complex nonlinear functions with little complexity.

2. Research Challenges

The basic research issue that needs to be addressed with this work is how to design under conflicting objectives. In other words, when the design parameters (or constraints) are uncertain as well as directly affect the objective function, then how the decision should be taken and how much space available for creativity. To find answers to these questions, experiments are performed for evaluating the capacity of air-cooler reservoir, and the research questions were specifically:

1. Reservoir capacity conflicts due to two parameters, nominal air capacity and cooling capacity. Between these two parameters a mathematical model may not remain valid for all the cases due to change in environmental conditions.

2. When experts are asked to design air cooler reservoirs, the capacity assessments are provided just in terms of one linguistic term; mostly like, high / medium / low or adequate / inadequate. To capture the accurate numeric value of the linguistic term, the decision making is a typical task.

3. Related Work

Hsiao (1998) proposed a decision-making method by quantifying the correlations between human sensations and the physical characteristics of products using fuzzy logic analysis. This technique supported the designers to create products that best satisfy the customers' requirements. Based on the distributed fuzzy models and fuzziness of interactions, a fuzzy computational approach for product configuration was developed by Ostrosi et al. (2012). This work delivered a formal approach that corresponds better to intelligent configuration design. The use of comparative linguistic expressions based on context-free grammars has been applied in many areas for linguistic problem. Lui & Rodríguez (2014) improved the capturing of linguistic information in decision making by introducing a set based on hesitant fuzzy linguistic terms. This was effective when experts hesitate to express their assessments due to several linguistic terms. This work facilitates experts with enhanced flexibility while presenting comparative linguistic expressions that are close to human beings' cognitive model, by using context-free grammars.

4. Fuzzy Logic Approach

The overall approach for product design under uncertainty is based on fuzzy logic approach. Fuzzy logic is based on the observation that people make decisions that are based on imprecise and unclear numerical information (Daws et al., 2009). It allows the system design by logic equations rather than complex differential or mathematical equations. Fuzzy logic has flexibility to manage different types of problems in engineering design and is a powerful tool to deal with the imprecision in design (Vanegas & Labib 2005). Wood et al. (1900), concluded that fuzzy set calculus is better for design problems involving imprecision because it is well organized and efficient than probability calculus and provides more information. Thurston and Carnahan (1992) concluded that fuzzy set theory should be used in the initial design phase. Here, we can deduce that if sufficient data to build accurate probabilistic models of uncertainties are not available, then fuzzy logic is better. A fuzzy rule based system consists of four parts: fuzzifier, knowledge base, inference engine and defuzzifier as shown in Fig. 2.The framework for fuzzy product design under uncertainty is shown with the help of Fig. 3. This framework, although, applicable to all cases of product design, but is more suited to engineering design problems. The framework consists of four stages. The first two stages address design related issues while the other two are concerned with the fuzzy aspects. According to Fig. 3, the fuzzy product design process under uncertainty can be briefly described as follows:

1. Define the design problem: The first critical step in successful implementation of the design method is to identify and clearly define the specific design problem. It is essential to clearly understand the problem so that all the associated parameters are considered properly.
2. Collect relevant facts and figure: Once the problem is defined, it is relatively easy to decide what are the conflicting parameters or which factor affects the desired parameters the most. Accordingly all the relevant facts and figures are recorded and sets made.
3. Construct membership function: Fuzzy membership functions model the uncertainty and imprecision, and expresses linguistic expressions comparatively. The data classified in the form of sets is now analyzed for its strengths and weaknesses and accordingly its membership function is defined. This degree of membership function is generally taken in the range [0, 1].
4. Construct IF-THEN rules: The design knowledge is represented by a set of IF-THEN rules and data as a set of facts related to the given situation. An expert usually expresses the design solution in the form of a fuzzy statement e.g. 'in such-and-such situation, I do so-and-so' (Negnevitsky, 2005). These expressions can be represented quite conveniently by IF-THEN rules.
5. Convert crisp value into fuzzy value: The crisp input is always a numerical value. Here, the information considered is uncertain, imprecise and incomplete hence the range of the universe of discourses can be determined by expert judgments and shown in fuzzy sets. By expert analysis, crisp values are converted into fuzzy sets and without a clear defined boundary. It can contain elements having varying degree of membership according to their strengths and weaknesses.

6. Evaluate the rules in the rule base: This step interprets user defined rule and assigns output value. For joining of two or more conditions, fuzzy operator “AND” and “OR” are used. This step decodes overall rules to obtain final output.

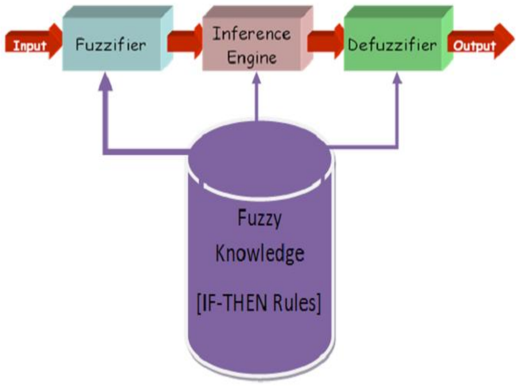

Figure 2. Fuzzy Inferencing System

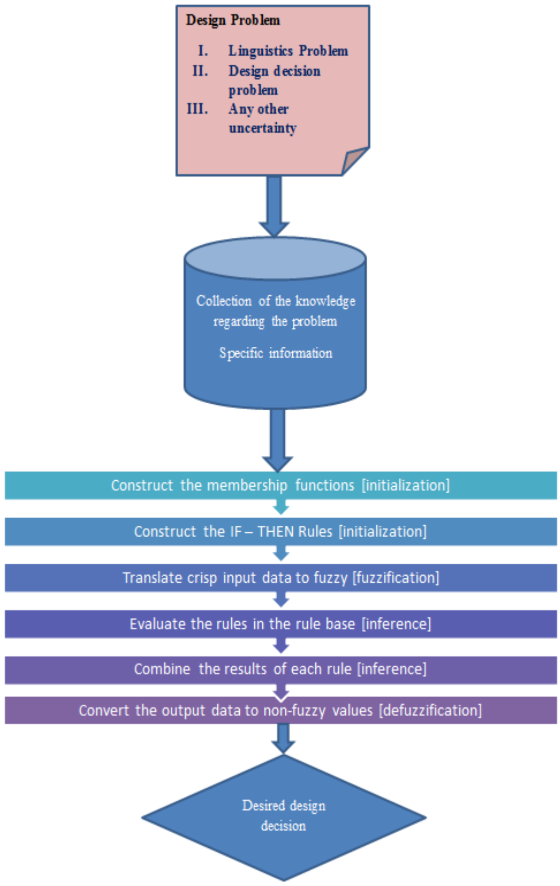

Figure 3. Fuzzy product design under uncertainty

7. If rules containing disjunctions, OR, are evaluated using the UNION operator. Fuzzy expert systems typically make use of the following classical fuzzy operation for union:
   μ AUB (x) = max [μA(x), μB(y)]
8. Where μAUB is the union of the output values from membership functions of μA(x) and μB(y); μA(x) is the output value for the membership function of x on A and μB(y) the output value of the membership function of y on B. Similarly, if AND fuzzy operation is used, fuzzy rules are evaluated using the intersection operator.
   $\mu A\cap B(x) = \min [\mu A(x), \mu B(y)]$
9. Combine the results of each rule: The output of different rules must be combined before defuzzification. Inference engine handles the way in which the rules are combined by mapping from a given input space to output space. The mapping then provides a transparent system for decision making. The process of fuzzy inference includes the membership functions, fuzzy logic operators and IF-THEN rules (Carrasco et al. 2002).
10. Convert the output data to non-fuzzy values: After the inference step, the result is generally a fuzzy value which is not very clear. Hence, with the help of fuzzy inference, the fuzzy set is converted into a crisp value, for the desired design decision.
11. Design Decision: According to fuzzy rule relevant to the design decision, different outputs are accurately shown for different inputs. This provides design direction to the designer where inputs are imprecise or contradictory, and thus, provides flexibility for the best design decision.

5. Application

Based on the method proposed above, design under uncertainty of an evaporative cooler has been developed with the help of MATLAB® fuzzy tool. Evaporative cooler design depends on the technical parameters like cooling pad thickness, water reservoir size, blade size, fan speeds, horsepower, etc. To reduce the design risk, companies need to evaluate the design constraints carefully and make accurate decisions regarding to the reservoir capacity of the evaporative cooler. In this work, two technical parameters i.e. (a) nominal air capacity and (b) cooling capacity are considered to evaluate the optimal capacity of air cooler reservoir. The crisp values of these two technical parameters are first converted to fuzzy values by using the membership functions (MF) of the appropriate sets. The nominal air capacity can be high, medium, and low; while the cooling capacity can be defined as adequate and inadequate. In the available literature, the output (reservoir capacity) is defined as crisp values and in this work; they are converted to fuzzy values of high, medium and low. Once the input and output variables, and MF are defined, IF-THEN rule-base is designed based on expert knowledge. The inference engine simulates the human knowledge through fuzzy sets obtained by inputs provided and IF-THEN rules. The results are then combined into a logical summation for each membership function. To obtain the final output in terms of crisp value, defuzzification is done to the fuzzy results obtained. The steps of the evaporative cooler reservoir capacity design under uncertainty are described as follows: The first step is to convert the crisp inputs into fuzzy. Since there are two inputs, there would be two crisp values to be converted into fuzzy. The first value is nominal air capacity (m3/hr) and the second value is cooling capacity (m3/hr). The fuzzy values for these crisp values can be generated by using the membership functions of the appropriate sets. The crisp values for cooling capacity are converted into fuzzy values as inadequate and adequate; with their fuzzy range [0-120] and [80-170] (m3/h) respectively. Visual representation of this process by defining membership functions is shown in Fig. 4. Similarly, the crisp values for nominal air capacity are converted into fuzzy values as, high, medium and low; with their fuzzy range; [3500-5000], [1500-4000] and [0-2000] (m3/hr) respectively and its visual representation is shown in Fig. 5.

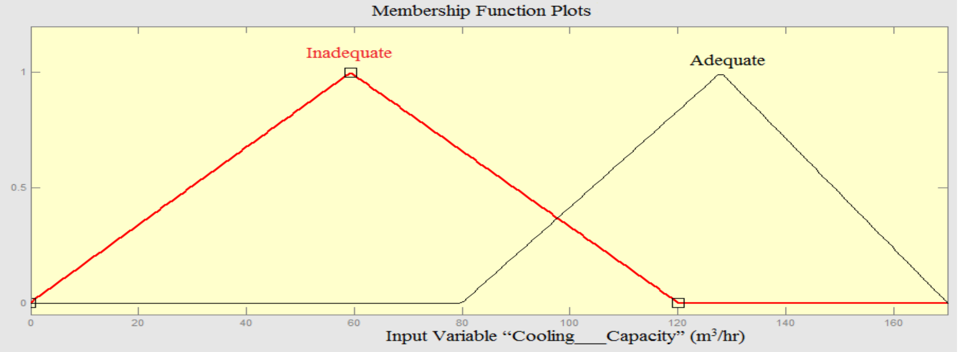

Figure 4. Membership function for cooling capacity (Input Subsets)

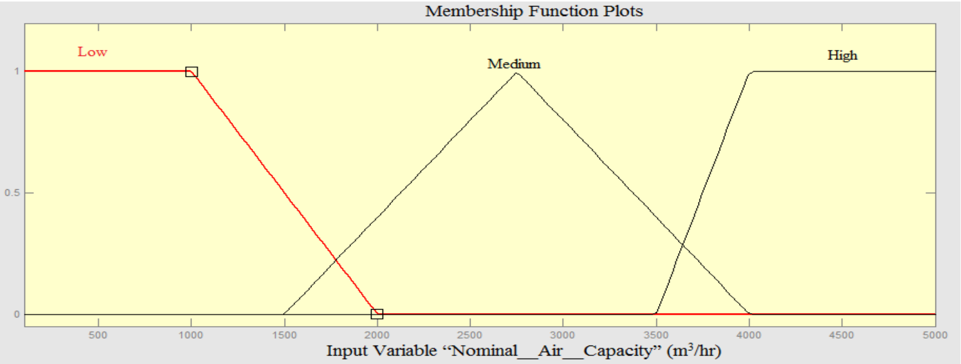

Figure 5. Membership function for nominal air capacity (Input Subsets)

In the second step, the desired output for the reservoir capacity as per the expert feedback / literature review in terms of fuzzy values high, medium and low; are in the fuzzy range of [30-60], [10-40] and [0-20] (liters) respectively. Figure 6 shows the corresponding membership functions.

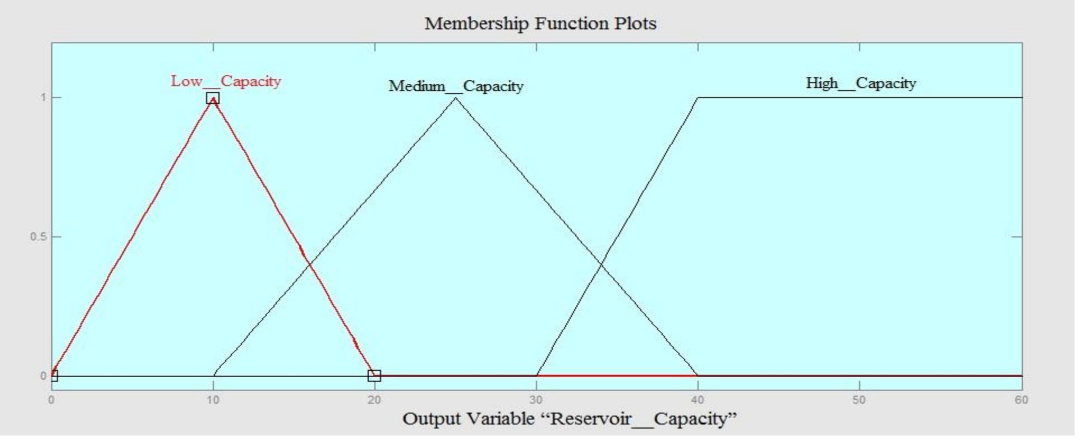

Figure 6. Membership function for reservoir capacity (Output)

The third step in building a fuzzy system is to define the fuzzy rules. Table 1 shows fuzzy rules associate the evaporative cooler reservoir capacity with the nominal air capacity and cooling capacity.

Table 1. Fuzzy Rule Base

S. No	Cooling Capacity	And / Or	Nominal air capacity	Then	Reservoir Capacity
1	Adequate	And	Low	Then	Medium
2	Adequate	And	Medium	Then	Medium
3	Adequate	And	High	Then	High
4	Inadequate	And	Low	Then	Low
5	Inadequate	And	Medium	Then	Medium
6	Inadequate	And	High	Then	High
7	Adequate	Or	Low	Then	High
8	Adequate	Or	Medium	Then	High
9	Adequate	Or	High	Then	High
10	Inadequate	Or	Low	Then	Low
11	Inadequate	Or	Medium	Then	Medium
12	Inadequate	Or	High	Then	High

The fourth step includes evolution of rules. Figure 7 shows one such rule i.e. If [cooling capacity is adequate] and [nominal air capacity is high], Then [reservoir capacity is medium]. Here, as "AND" fuzzy operation is used, hence fuzzy rules are evaluated using the intersection operator. In fuzzy rules, conjunctions are evaluated using the "Intersection" operator. For example;

$$\mu A\cap B(x) = \min [\mu A(x), \mu B(x)]$$

μ Reservoir Capacity Medium = Min [μ Cooling Capacity → adequate (= 0.2), μ Nominal air capacity → High (= 0.3)]

In other words,

μ Reservoir Capacity = Medium = Min [0.2, 0.3]

μ Reservoir Capacity = Medium = 0.2

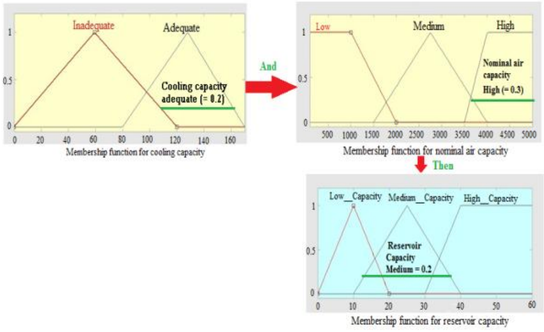

Figure 7. Evolution of the rule (through Inference engine)

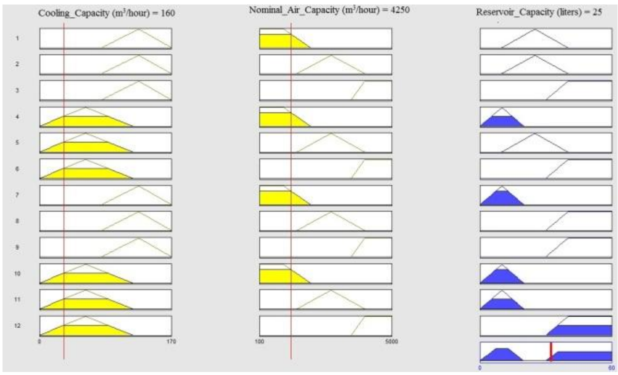

Figure 8. Design decision criteria (Output)

To find the crisp value of the reservoir capacity, the center of gravity (COG) for the area cooling capacity, nominal air capacity and reservoir capacity are evaluated for adequate, high and medium membership function respectively and given as:

$$\text{COG}=\frac{\sum_{x=a}^{b}\mu_A(\text{X})\text{x}}{\sum_{x=a}^{b}\mu_A(\text{X})}$$

For the data considered for the present application as per the experience of the designers, the COG for cooling capacity, nominal air capacity and reservoir capacity is evaluated as 160 m^3/hour, 4250 m^3/hour and 25 liters respectively. Therefore, for the fuzzy rule considered i.e. “If [Cooling Capacity is adequate with membership function 0.2] and [Nominal air capacity is high with membership functions 0.3], Then [Reservoir capacity is medium with membership function 0.2]”, the reservoir capacity would be 25 liters. This helps in providing a design direction and creativity space to designers for the design of the evaporative cooler where the reservoir capacity was uncertain. Chakrabarti (2011) has mentioned that creative success in design has three major areas of influence: knowledge, motivation, and opportunity. Since motivation and opportunity depends on knowledge, hence, in this work the fuzzy knowledge is applied for establishing relations among conflicting objectives e.g. reservoir capacity, nominal air capacity and cooling capacity. In this work, rule based fuzzy knowledge, can aid users in the scenarios, where it is tough to have sound reasoning skills to take decisions amidst conflicting objectives. This in turn, influences positively the execution of creative design tasks, which in turn depends on focused design approach. Further, as indicated by Chakrabarti (2013), two classes of knowledge exist. They are domain knowledge and process knowledge. Domain knowledge deals with hands-on abilities, observational/experiential knowledge, and hypothetical/mathematical knowledge. Process knowledge comprises independent thinking, imagination, and intuition. The outcomes of this research can be used for providing domain knowledge through inferences drawn from observational/experiential knowledge of conflicting design objectives. For example, for the experiment presented in the manuscript, if the conflicting objectives are not resolved, a designer would take decision on reservoir capacity based on his/her intuitive ability. Besides, designer can accordingly decide the shape of the reservoir, which may be cubical, spherical, cylindrical, etc. As all creative works are consequences of clarity and extension of a centered plan, hence, if the designer select appropriate reservoir capacity as suggested by the fuzzy approach, it can be more advantageous to the proposed creative design solution.This system also provides enough flexibility to the designer to make design decisions with regard to the reservoir capacity. This approach is capable of evaluating accurately reservoir capacities for different inputs and helps make sound selection of optimum set, as shown in Fig. 8. This process reflects a variety of decision making criteria, as per the customer requirements.

6. Conclusion

This paper presents an creative approach for making a valid and feasible design decision, when inputs are imprecise or contradictory. In fact, imprecision and uncertainty occur all over the design cycle. The proposed fuzzy design approach represents the decision taking power in a better way and is automated. It also provides enough flexibility to the designer for design creativity. This approach can be conveniently applied to many other product design problems than just evaporative cooler design. It can also be used for design optimization. There is a need to extend this approach to handle linguistic, aesthetic and fashion uncertainties specifically for the product design. This approach help develop a dedicated tool for handling new product design under uncertainty and allow to take advantage of the creativity-based design process to achieve the goals of innovative product design.

Referances

Carrasco, E. F., Rodrıguez, J., Punal, A., Roca, E., & Lema, J. M. (2002). Rule-based diagnosis and supervision of a pilot-scale wastewater treatment plant using fuzzy logic techniques. *Expert Systems with Applications*, 22(1), 11-20.

Chakrabarti, A. (2011). Motivation as a major direction for design creativity research. *In Design creativity 2010* (pp. 49-56). Springer London.

Chakrabarti, A. (2013). Understanding influences on engineering creativity and innovation: a biographical study of 12 outstanding engineering designers and innovators. International Journal of *Design Creativity and Innovation*, 1(1), 56-68.

Chen, L. H., & Ko, W. C. (2009). Fuzzy approaches to quality function deployment for new product design. *Fuzzy sets and systems*, 160(18), 2620-2639.

Daws, K. M., AL-Dawood, Z. I., & AL-Kabi, S. H. (2009). Fuzzy Logic Approach for Metal Casting Selection Process. *JJMIE*, 3(3).

Hsiao, S. W. (1998). Fuzzy logic based decision model for product design. *International Journal of Industrial Ergonomics*, 21(2), 103-116.

Li, H., & Azarm, S. (2000). Product design selection under uncertainty and with competitive advantage. *Journal of Mechanical Design*, 122(4), 411-418.

Li, Y., Tong, S., Li, T., & Jing, X. (2014). Adaptive fuzzy control of uncertain stochastic nonlinear systems with unknown dead zone using small-gain approach. *Fuzzy Sets and Systems*, 235, 1-24.

Lin, K. H., Shih, L. H., Cheng, Y. T., & Lee, S. C. (2011). Fuzzy product line design model while considering preference uncertainty: A case study of notebook computer industry in Taiwan. *Expert Systems with Applications*, 38(3), 1789-1797.

Liu, H., & Rodríguez, R. M. (2014). A fuzzy envelope for hesitant fuzzy linguistic term set and its application to multicriteria decision making. *Information Sciences*, 258, 220-238.

Negnevitsky, M. (2005). Artificial intelligence: a guide to intelligent systems. Pearson Education.

Oh, J., Yang, J., & Lee, S. (2012). Managing uncertainty to improve decision-making in NPD portfolio management with a fuzzy expert system. *Expert Systems with Applications*, 39(10), 9868-9885.

Ostrosi, E., Haxhiaj, L., & Fukuda, S. (2012). Fuzzy modelling of consensus during design conflict resolution. *Research in Engineering Design*, 23(1), 53-70.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). Engineering design: a systematic approach (Vol. 157). *Springer*.

Thurston, D. L., & Carnahan, J. V. (1992). Fuzzy ratings and utility analysis in preliminary design evaluation of multiple attributes. TRANSACTIONS-AMERICAN SOCIETY OF MECHANICAL ENGINEERS JOURNAL OF MECHANICAL DESIGN, 114, 648-648.

Vanegas, L. V., & Labib, A. W. (2005). Fuzzy approaches to evaluation in engineering design. *Journal of mechanical design*, 127(1), 24-33.

Wood, K. L., Antonsson, E. K., & Beck, J. L. (1990). Representing imprecision in engineering design: comparing fuzzy and probability calculus. *Research in Engineering Design*, 1(3-4), 187-203.