A Design Process Framework to Deal with Non-functional Requirements in Conceptual System Designs

Bugra Alkan, Seth Bullock, Kevin Galvin and Angus Johnson

Abstract To simultaneously satisfy the user needs and project-specific technical requirements, it is imperative that complex engineering systems are designed using contemporary, systematic approaches. This study presents a framework that combines Axiomatic Design and Fuzzy Analytic Hierarchy Process to ensure that designers can concurrently satisfy the functional and non-functional requirements along with the design constraints of conceptual system designs. A conceptual design case of an autonomous battery charging system for Unmanned Aerial Vehicles is presented as an illustrative case study. The results showed that the approach can aid decision-making processes by systematic evaluation and comparison of conceptual designs such that the selected solutions satisfy user needs whilst also realising both functional and non-functional requirements of the system.

1 Introduction

Non-functional requirements (NFRs) are considered as a very important aspect of engineering design. In order to have a good system design it is imperative that the NFRs are well-structured [1]. The primary difference between an NFR and FR is that FRs dictates what system needs to do, whereas, NFRs imposes constraints on how the system should work. Typically, NFRs are not associated with quantitative

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measures and are difficult to analyse and are excluded from specifications [2, 3]. Although, in software engineering field, there are approaches that consider NFRs, predominantly, the FRs are given more importance [4].

This article presents a design process framework based on the Axiomatic Design (AD) to integrate NFRs into the mapping between the problem domain and the solution domain. AD, chiefly introduced by Nam P. Suh [5], offers a systematic approach to guide system development projects by solely following the design axioms. One of the important restrictions of AD is the absence of non-functional requirements (NFRs) of the system (e.g. scalability, reliability, flexibility, readability, etc.) during the conceptual design phase. To address this problem, AD's design matrix is revisited to include the mapping between a complete set of requirements (functional and non-functional) and corresponding design parameters (physical domain). Moreover, the Fuzzy Analytic Network Process (F-AHP) is used as a complementary approach to AD to integrate both FRs and NFRs into the decision-making processes of the conceptual design stage. The F-AHP complements the new design matrix and helps identify the most suitable solution among design alternatives that satisfy design requirements (DRs).

2 Axiomatic Design (AD)

AD is a systematic design methodology primarily proposed by Nam P. Suh of Massachusetts Institute of Technology (MIT) in the early 70s. AD is a generic approach based on domain and design axioms. It allows decomposition of systems of any scale into their constituent elements by mapping FRs to Design Parameters (DPs) through the zigzagging process [6]. In the AD, there are two design axioms: independence axiom and information axiom [7]. The independence axiom ensures that FRs of a system are independent from each other (i.e. uncoupled, decoupled design), whereas, the information axiom minimises the information content of a design. According to Suh [5], the information content of a design is strongly correlated with the complexity of the design process itself, therefore, should be eliminated. Hence, the design axioms in the AD primarily aim at eliminating the real complexity (i.e. uncertainty) in the design process, thereby offering a robust design that can satisfy all FRs while exist within the predefined design range [8]. Please note that they are also useful in comparing alternative designs.

AD considers the design process within four interrelated domains: functional, physical, customer, and process domains. The design artefact is represented in each of these domains with a set of customer requirements (CRs), FRs, DPs and process variables (PVs), respectively. These sets are represented in a hierarchy structured depending on the abstraction levels of domain variables. As a whole, this domain-hierarchy structure guides designers in following multiple two orthogonal thinking directions, thereby leading to a systematic reasoning. AD is also characterised by the zigzagging process, where different types of design elements across the adjacent domains can be mapped. The design matrix A that determines the location

of the couplings between FRs and DPs is established. AD enforces that the independence axiom should always be satisfied while generating the design matrix *A*. The designs that maintain the independence axiom are called as *good* or *acceptable* design. There are two types of *good* design; uncoupled and de-coupled designs, whereas the coupled design is considered as *bad* design. The design pattern can be readily extracted from the design matrix [A] in the equation FRs = [A] DPs.

$$
\begin{bmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_n \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1m} \\ A_{21} & A_{22} & \dots & A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \dots & A_{nm} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_m \end{bmatrix} \tag{1}
$$

If the matrix [A] is an orthogonal matrix, i.e. $A_{ij} = 0$ for i$\neq$j, the design is considered as an uncoupled design. If all the entries above the main diagonal of the matrix [A] are zero, then the design is considered as a decoupled design. All other design patterns for the matrix [A] are defined as a coupled design which requires further improvements and modifications before proceeding through the zigzagging process. To express what kind of relation the FRs and DPs have with each other, symbols such as *0*, *X* and *C* can be used to describe "*no relationship*", "*unidirectional relationship*" and "*coupled relationship*", respectively.

3 Research Methodology

Both FRs and NFRs play an important role during the design stages of engineering systems. NRFs help in achieving the reliability, availability and performance of the system, and ensure that the system follows legal and compliance rules [9]. Although the AD is a solid framework for the design process, it is considered as limited as it does not give a full consideration to NFRs. This limitation has also been addressed in [10]. In this section, we present an iterative design framework that includes the non-functional behavioral design concerns into the engineering design process. The approach integrates the F-AHP method into the AD process enabling the selection of a solution that is more preferable from an existing set of solutions that have been determined by AD. **Figure 1** illustrates the schematic flow diagram of the proposed approach.

3.1 Proposed extensions to AD

In this research, AD is extended to include the relationships between FRs, NFRs and DPs with an aim to help in selecting the best design parameters from the physical
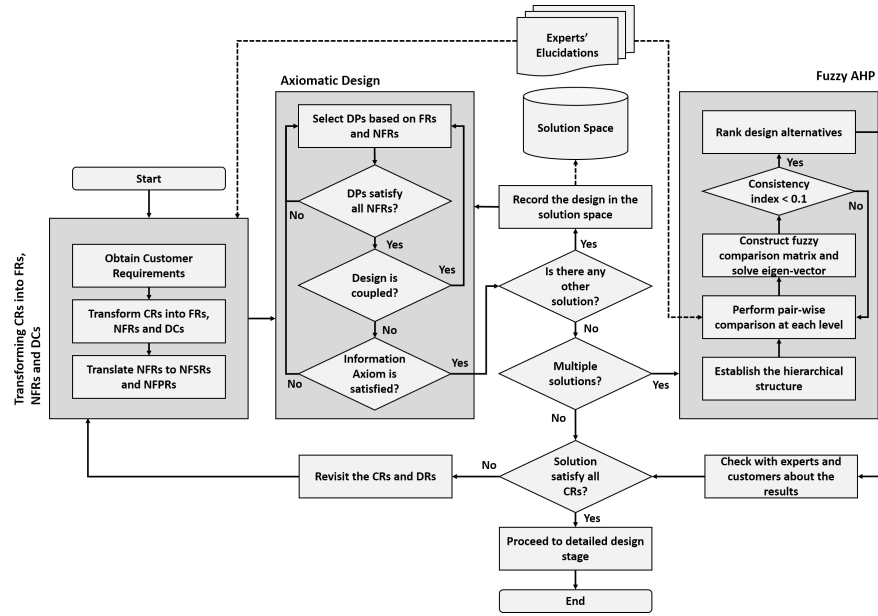
Fig. 1 The flow-chart of the approach.

domain. Here, NRFs are treated as an additional set of FRs that can translate CRs to both DPs and PVs from physical and process domains, respectively (**Figure 2**).
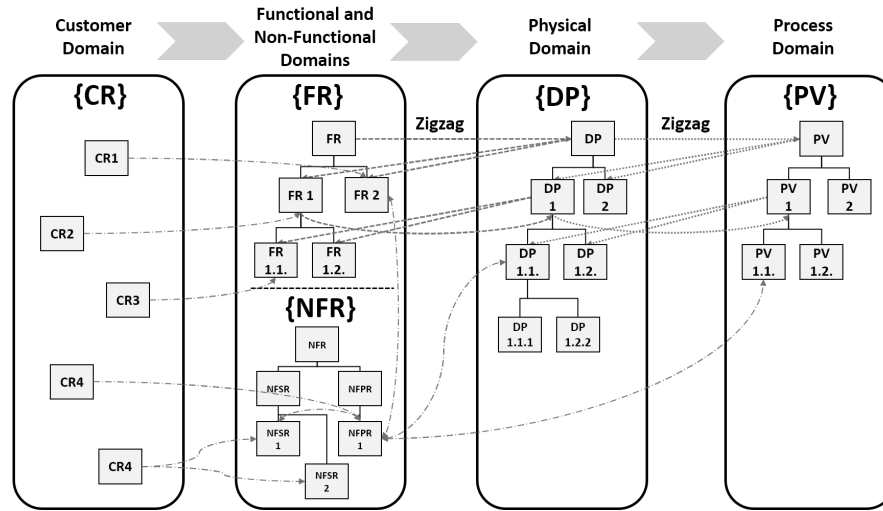

Fig. 2 Extended design domains of AD.

NFRs impose constraints on how the system works, and address the general aspects of the system, e.g. performance, cost, security, maintainability, etc. The AD process generally commences with collecting information pertaining to the system or product that needs to be designed. This information, gathered from the customers and stakeholders, is then mapped and expressed as functional and non-functional requirements. However, this process of mapping the information is not within the scope of the study. According to AD theory, DPs from the physical domain are selected using the zigzagging methodology and functional requirements are decomposed from the higher level to lower levels. In the proposed model, the functional requirements are bolstered with the non-functional requirements to support the selection of design parameters from the physical domain. Here, it is assumed that each NFR is defined with a maximum clarity at the lowest level of abstraction.

The design matrix in AD theory is extended to be a three-dimensional matrix as shown in **Figure** 3. This three-dimensional design matrix is composed of pair-
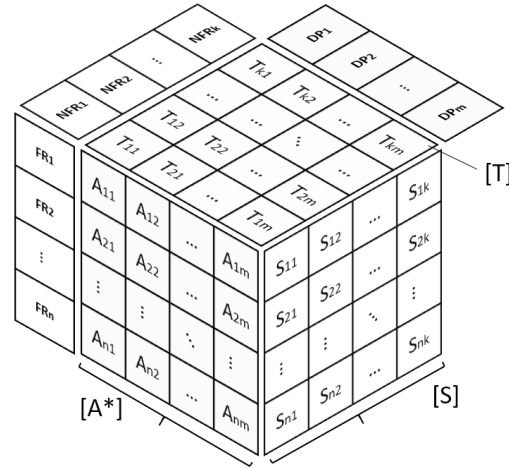
Fig. 3 The three-dimensional design matrix.

wise domain mapping matrices. The inter-dependencies between FRs, NFRs and DPs are represented by a modified design matrix (A^*). The second block matrix, S, is used visualise the dependencies between FRs and corresponding non-functional performance constraints. Elements of this matrix are defined as follows.

$$S_{ij} = \begin{cases} X & \text{if } i^{th} \text{ FR has a non-functional performance constraint } j^{th} \text{ NFR,} \\ 0 & \text{otherwise.} \end{cases}$$

The third design matrix, T, is used to define the DPs that are required to satisfy the given set of NFRs, and captures the inter-dependencies between physical and non-functional design domains. Similarly, the elements of T matrix can be defined as follows:

$$T_{ij} = \begin{cases} X & \text{if } i^{th} \text{ DP does satisfy the } j^{th} \text{ NFR,} \\ 0 & \text{otherwise.} \end{cases}$$

To fully define the relations between functional and physical domains, A and T matrices are merged into a 2x1 block design matrix DM as follows:

$$\begin{bmatrix} FR1 \\ FR2 \\ . \\ FR_n \\ NFR1 \\ NFR2 \\ . \\ NFR_k \end{bmatrix} = [DM][DP] = \begin{bmatrix} A_{11} & \tilde{A}_{12} & ... & \tilde{A}_{1m} \\ \tilde{A}_{21} & \tilde{A}_{22} & ... & \tilde{A}_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{A}_{n1} & \tilde{A}_{n2} & ... & \tilde{A}_{nm} \\ T_{11} & \tilde{T}_{12} & ... & \tilde{T}_{1m} \\ \tilde{T}_{21} & \tilde{T}_{22} & ... & \tilde{T}_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{T}_{k1} & \tilde{T}_{k2} & ... & \tilde{T}_{km} \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ . \\ DP_m \end{bmatrix} \qquad (2)$$

According to AD, the original design matrix A should always satisfy the independence axiom. In addition to this, the block matrix T, should not have any null rows; meaning that each NFR should be satisfied by at least one DP. The T matrices with at least a null row are considered as a *invalid solution*. Invalid solutions require further investigations and alterations.

3.2 Design selection via Fuzzy Analytic Hierarchy Process

The AD approach can be concluded with multiple design solutions. For such cases, we need to use a decision-making method to choose the best design among many alternative design solutions that can satisfy both FRs and NFRs. In the proposed framework, Fuzzy Analytic Hierarchy Process (F-AHP) method is used to address this problem. This method is chosen over AHP and ANP (see [11]) as it is better suited to handle the fuzziness associated with the conceptual design phases. F-AHP uses the concepts of fuzzy set theory and hierarchical structure analysis to deal with complex multi-criteria decision-making problems [12].

The F-AHP is integrated with AD as seen in **Figure 4** which provides an example of the decision making hierarchy. In here, NFRs are considered as criteria for decision-making, whereas, DPs are the parameters to be selected from a set of alternative solutions (sol_1, sol_2,...,sol_m). A detail look on the step-by-step implementation of F-AHP can be found in [12]. In here, it is briefly explained within five steps. In *the first step*, the performance scores of network elements are compared within the same level of hierarchy. Linguistic terms are used to indicate the relative strength of each pair of elements. *The second step* involves the construction of fuzzy comparison matrices using fuzzy numbers. Accordingly, the fuzzy judgment matrix $\tilde{B}$ is constructed as given below:
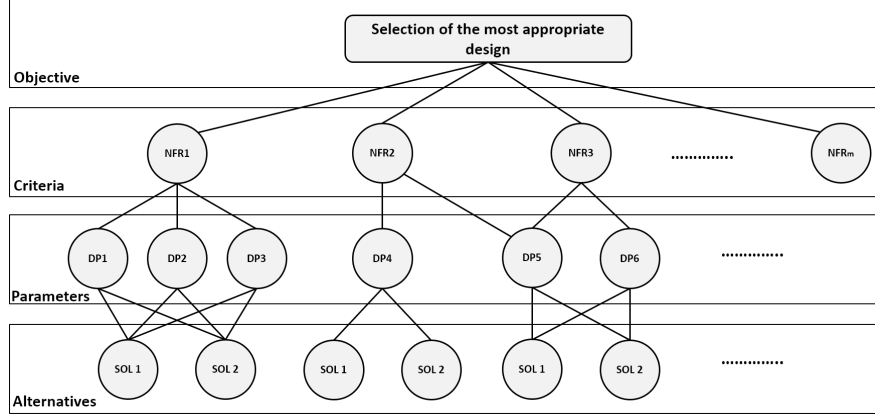
Fig. 4 An example decision-making structure for managing NFRs.

$$\tilde{B} = \begin{bmatrix} \tilde{b}_{11} & \tilde{b}_{12} & ... & \tilde{b}_{1n} \\ \tilde{b}_{21} & \tilde{b}_{22} & ... & \tilde{b}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{b}_{n1} & \tilde{b}_{n2} & ... & \tilde{b}_{nn} \end{bmatrix} \tag{3}$$

where, $b_{ij}^{\tilde{\alpha}} = 1$, if $i = j$, and $b_{ij}^{\tilde{\alpha}} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ or $\tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}$, if $i \neq j$. In *the third step,* the fuzzy eigenvalues are solved. A fuzzy eigenvalue, $\tilde{\lambda}$; is a fuzzy number solution to $\tilde{B}\tilde{x} = \tilde{\lambda}\tilde{x}$, where $\tilde{\lambda}_{max}$ is the largest eigenvalue of $\tilde{B}$ and $\tilde{B}$ is a non-zero $n \times 1$ fuzzy vector containing fuzzy number $\tilde{x}$. To perform fuzzy multiplications and additions by using the interval arithmetic and α-cut, the equation $\tilde{B}\tilde{x} = \tilde{\lambda}\tilde{x}$ is equivalent to:

$$[b_{i1l}^{\alpha} x_{1l}^{\alpha}, b_{i1u}^{\alpha} x_{1u}^{\alpha}] \oplus \cdots \oplus [b_{inl}^{\alpha} x_{nl}^{\alpha}, b_{inu}^{\alpha} x_{nu}^{\alpha}] = [\lambda x_{il}^{\alpha}, x_{iu}^{\alpha}] \tag{4}$$

$$\tilde{B} = [\tilde{b}_{ij}^{\alpha}], \tilde{x}^t = (\tilde{x}_1, \ldots, \tilde{x}_n) \tag{5}$$

and $\tilde{b}_{ij}^{\alpha} = [b_{ijl}^{\alpha}, b_{iju}^{\alpha}], \tilde{x}_{ij}^{\alpha} = [\lambda_l^{\alpha}, \lambda_u^{\alpha}]$ for $0 < \alpha \leq 1$ and all i, j, where i=1,2,...,n, j=1,2...,n. The confidence of the decision-maker's preference is a part of α-cut. The index μ is the index of optimism. A higher μ indicates a higher degree of optimism over the judgements. This index is a linear convex combination defined as: $\tilde{b}_{ij}^{\alpha} = \mu \tilde{b}_{ijl}^{\alpha} + (1 - \mu) \tilde{b}_{ijl}^{\alpha}, \forall \alpha \in [0, 1]$. When α is fixed, the following matrix can be obtained after setting the index of optimism, μ, to estimate the degree of satisfaction:

$$\tilde{B} = \begin{bmatrix} \tilde{b}_{11}^{\alpha} & \tilde{b}_{12}^{\alpha} & ... & \tilde{b}_{\alpha}^{1n} \\ \tilde{b}_{21}^{\alpha} & \tilde{b}_{22}^{\alpha} & ... & \tilde{b}_{2n}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{b}_{n1}^{\alpha} & \tilde{b}_{n2}^{\alpha} & ... & \tilde{b}_{nn}^{\alpha} \end{bmatrix} \tag{6}$$

The eigenvector comprises of the priorities of the compared objects and is calculated by fixing the μ value and identifying the maximal eigenvalue. *The fourth step* involves the calculation of the consistency ratio (CR) for matrices and overall inconsistency for the hierarchy. An estimation of the consistency of the pairwise comparisons is provided by the Consistency ratio as shown in equation below.

$$CR = CI/RI, \quad CI = \frac{\lambda_{max} - n}{n - 1} \tag{7}$$

where *CI* is the consistency index, *RI* is a randomly generated consistency index, and λ_{max} is the largest eigenvalue of the n-order matrix. In ideal cases, CR should be less than 0.10. Conclusively, the last step is the computation of the priority weight of the considered alternatives. This is achieved by the multiplication of the matrix of evaluation ratings by the vector of attribute weights and summing over all attributes. From the obtained results, the solution with the highest score is presented to the decision maker.

4 Case Study

In this section, the proposed approach is employed to automated battery charging systems. An automated battery charging system is a ground service station for unmanned aerial vehicles (UAVs) that replenishes vehicle batteries without any human intervention. To simplify the design process, a total of four high-level FRs and NFRs are selected as design requirements to be fulfilled.

- FR1 Provide an identifiable landing,
- FR2 Charge UAV batteries,
- NFR1 Convertibility - provide quick changeovers,
- NFR2 Portability - ease of transportation.

4.1 AD process

An AD process is carried out using two charging platform concept models (**Figure 5**) that are taken from [13]. The former design (Design A) consists of rectangular wire mesh bands arranged in parallel on a flat rectangular mat and the latter design consists of hexagonal battery cells and operates independently of the helicopter landing orientation. The charging terminals of Designs A and B are present on the wire mesh and the hexagonal battery cells, respectively. Here, we only consider a zigzagging process between physical and functional domains within two decomposition levels. Please note that the proposed approach builds on top of the existing study proposed in [13] by the novel addition of two NFRs to the already available FRs in the AD process. FR1 requires a landing platform (DP1). The first functional
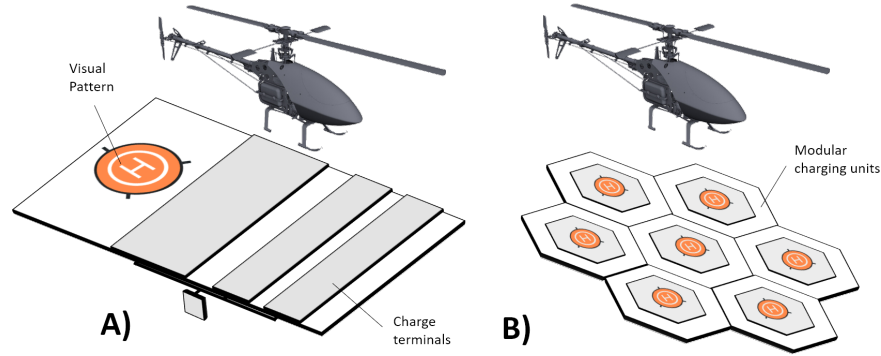
Fig. 5 Schematic representations of the design options: *a*) Design A, **b**) Design B (This figure is prepared using the information/pictures provided in [13].)

requirement (FR1.1) dictates that the platform dimensions should consider the dimensions of the UAV and the navigation system error during landing. Moreover, the current position of the platform should be communicated to the navigation system for allowing the successful landing of the UAV (FR1.2). In the Design A, it is achieved through visual patterns that can be recognised by the UAV at a distance. On the other hand, the Design B realises this FR through a direct wireless communication. To charge UAVs (FR2), the battery charging system requires a charging system (DP2). To realise this, firstly, a safe interface between the electronics of the system and the UAV must be established (FR2.1). In the first design, this is established via physical terminals on both the platform and the UAV, therefore, the landing position of the UAV must be checked before the electrical transmission is made (FR2.2). The first design satisfies this FR by a position identification system. In the second design, the platform control unit scans its constituent hexagon cells to identify which ones are host to the UAV. In both designs, the charging process (FR2.3) is done via an electronics system that can able to detect *i*) charge needs of the UAV, *ii*) status of the charging process, and *iii*) charging faults (DP2.3). NFR1 can be satisfied by a modular structure. The second design is a modular/extendable system (DP3 for the Design B): numerous helicopters can be charged simultaneously by adding more cells and charger devices. Contrary to this, the design A has failed to satisfy this requirement as it has a dedicated structure that does not allow any quick changeovers. Hence, this design should be considered as invalid for given NFRs. NFR2 requires a lightweight materials and/or compact structure that provides ease of transportation and storage. The first design has a foldable lightweight mat (DP3 for the Design A) that can be easily carried around. On the other hand, the second design provides a compact structure (DP4 for the Design B) that can be easily stored and transported. The AD design matrices *DM* for each solution are displayed in **Figure 6**. According to the results, the design A exhibits couplings between platform and charging system. This is due to the size of the terminals located on the mat naturally impact on

the size of the mat. The design of B, on the other hand, achieves this by decoupling these relationships through a modular approach.

Fig. 6 Design matrices of both design candidates (Sub-matrices *A* and *T* are marked as blue and purple, respectively.).

4.2 Selection of the optimal design via F-AHP

Let's assume that the concept models in the above example meet all FRs and the AD's independence axiom (i.e. de-coupled or uncoupled) in addition to fulfilling a new set of NFRs with minimum acceptable performance. In addition to these, the designer wants to compare the design solutions with respect to the degree to which they can satisfy the given set of NFRs. The NFRs for this case are selected as follows: NFR1 Affordability, NFR2 Maintainability, NFR3 Reliability, NFR4 Scalability, NFR5 Interoperability, NFR6 Security, and NFR7 Product weight. To do this, the F-AHP method is used with the AD process. In here, we have assumed two unique customer groups who want to achieve a suitable battery charging station design for hobby and military applications respectively. Each group has different preference with respect to NFRs.

The fuzzy comparison matrices of pairwise comparisons of NFRs for both customer groups are defined using triangular fuzzy numbers (TFN) with membership functions (as $\tilde{1}$:(1,1,1), $\tilde{3}$:(1,3,5), $\tilde{5}$:(3,5,7), $\tilde{7}$:(5,7,9), $\tilde{9}$:(7,9,11)) and are given in **Table 1** and **Table 2**, respectively. Then, the fuzzy comparison matrices for design alternatives with respect to each NFR are calculated. The normalised non-fuzzy relative weights of each alternative for each NFR are found and given in **Table 3**. CRs for all matrices are found to be lower than 0.1. From **Table 2**, the results of the F-AHP elicit that hobbysist prioritise affortability and product weight over other NFRs. In case of military application, it can be seen that reliability, scalability and

interoperability are prioritised. Consequently, it can be understood from **Table 3** that for hobby applications, Design A is more suitable based on the customer preferences, and in case of military applications, Design B is considered favourable.

Table 1 Fuzzy comparison matrix of NFRs with respect to the design selection using triangular fuzzy numbers - Preferences for hobby use (α-cut=0.5, μ=0.5).

	NFR1	NFR2	NFR3	NFR4	NFR5	NFR6	NFR7	Priorities	Rank
NFR1-Affordability	1	$\tilde{5}$	$\tilde{3}$	$\tilde{9}$	$\tilde{5}$	$\tilde{7}^{-1}$	$\tilde{1}^{-1}$	0.2791	1
NFR2-Maintainability	$\tilde{5}^{-1}$	1	$\tilde{1}^{-1}$	$\tilde{5}$	$\tilde{1}$	$\tilde{5}$	$\tilde{3}^{-1}$	0.1236	4
NFR3-Reliability	$\tilde{3}^{-1}$	$\tilde{1}$	1	$\tilde{3}$	$\tilde{3}$	$\tilde{9}$	$\tilde{3}^{-1}$	0.1653	3
NFR4-Scalability	$\tilde{9}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	1	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{9}^{-1}$	0.0245	7
NFR5-Interoperability	$\tilde{5}^{-1}$	$\tilde{1}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}$	1	$\tilde{3}$	$\tilde{5}^{-1}$	0.1021	5
NFR6-Security	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{9}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	1	$\tilde{9}^{-1}$	0.0264	6
NFR7-Weight	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{9}$	$\tilde{5}$	$\tilde{9}$	1	0.2791	1
							λ_{max}	7.7581	
							CI	0.1263	
							CR	0.0936 < 0.1 is ok	

Table 2 Fuzzy comparison matrix of NFRs with respect to the design selection using triangular fuzzy numbers - Preferences for military use. (α-cut=0.5, μ=0.5)

	NFR1	NFR2	NFR3	NFR4	NFR5	NFR6	NFR7	Priorities	Rank
NFR1-Affordability	1	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{7}^{-1}$	$\tilde{9}^{-1}$	$\tilde{7}^{-1}$	0.0244	7
NFR2-Maintainability	$\tilde{3}$	1	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{9}^{-1}$	$\tilde{5}^{-1}$	0.0608	6
NFR3-Reliability	$\tilde{5}$	$\tilde{3}$	1	$\tilde{3}$	$\tilde{3}^{-1}$	$\tilde{7}^{-1}$	$\tilde{3}^{-1}$	0.1292	3
NFR4-Scalability	$\tilde{3}$	$\tilde{1}^{-1}$	$\tilde{3}^{-1}$	1	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	0.0619	5
NFR5-Interoperability	$\tilde{7}$	$\tilde{3}$	$\tilde{1}^{-1}$	$\tilde{1}$	1	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	0.1220	4
NFR6-Security	$\tilde{9}$	$\tilde{9}$	$\tilde{7}$	$\tilde{5}$	$\tilde{5}$	1	$\tilde{3}$	0.3534	1
NFR7-Weight	$\tilde{7}$	$\tilde{5}$	$\tilde{3}$	$\tilde{5}$	$\tilde{5}$	$\tilde{3}^{-1}$	1	0.2483	2
							λ_{max}	7.6669	
							CI	0.1116	
							CR	0.0827 < 0.1 is ok	

Table 3 The results of the F-AHP approach (α-cut=0.5, μ=0.5).

	Normalized non-fuzzy relative weights of solutions for each NFR							Aggregated scores for each solution with respect to:	
	NFR1	NFR2	NFR3	NFR4	NFR5	NFR6	NFR7	Hobby Use	Military Use
Design A	0.844	0.253	0.253	0.117	0.253	0.253	0.747	0.553	0.382
Design B	0.156	0.747	0.747	0.883	0.747	0.747	0.253	0.447	0.618

5 Conclusion

This paper presents a design process framework that explicitly integrates NFRs into the AD process using an extended form of the design matrix identifying the solutions concerning NFRs. It also merged F-AHP method to support critical decision-making activities by considering the impact of NFRs. As a next step, the proposed framework will be improved by including a model for decomposition of NFRs during the zigzagging process, and continued to be validated using a number of real-world engineering design cases.

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