A combined Axiomatic Design-MCDA method for selecting medical systems operating on a common telemedicine platform

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Abstract. The Covid-19 pandemic has triggered a significant push towards the digitalization of the Italian healthcare system. The National Recovery and Resilience Plan (PNRR) has designed a Digital Health national platform that is implemented based on microservices. However, the technological heterogeneity of healthcare companies poses difficulties in using a common healthcare platform in terms of interoperability. The first issue is selecting, for each health protocol, the basket of medical systems to be adopted, which must be compatible with this infrastructure and appropriate for the operating context. In this article, the authors propose a methodology to select healthcare systems based on axiomatic design and MCDA techniques. The expected result is to identify, in the first phase, the set of functionally acceptable solutions, and in the second phase, to select the most suitable basket based on evaluation criteria that are not necessarily functional.

Keywords: Axiomatic design, information entropy, Healthcare digital transition

1 Introduction

The National Recovery and Resilience Plan (PNRR) aims to develop a national platform for Digital Health (**Figure 1**) based on micro-services, which will be made available to the various Italian regions. This initiative, funded by the European Union, aims to provide basic tools to all Italian healthcare companies to ensure that essential healthcare treatment levels, as guaranteed by the Constitution, are met. It should be noted that in Italy, the healthcare system is of the "universal type", which means that it is the responsibility of the public sector and managed by the regions. This has resulted in a diversification of the levels of service offered, with each region having specific systems within the scope of what is permitted by the Ministry of Health. This technological heterogeneity poses a critical issue in the use of a common health platform, as it presents challenges for the interoperability between different systems. Moreover, a study conducted on around 800 healthcare professionals from different healthcare companies has shown that only 3% of the interviewees use Telemedicine systems, particularly for consultation activities with colleagues. The collected data shows that only 18% of users have received dedicated training, highlighting the need for significant investment in technology and skills development to ensure the widespread diffusion of digital medicine. Therefore, a robust methodology is necessary to assist decision-makers in selecting the most suitable medical systems for the platform to meet the needs of patients and healthcare professionals. The methodology involves two parts: identifying admissible solutions, i.e. the compositions of medical devices that can be used for a specific health protocol, and selecting the most suitable solution for the operative context. The independence axiom constitutes a powerful tool to identify admissible baskets. However, for the second problem category, the information axiom may not be enough, and other selection tools, such as multi-decision analysis techniques criterion (MCDA), are required. The authors propose using AHP to define the relative importance of individual selection criteria, while the decision-making process is carried out based on the information entropy concept.

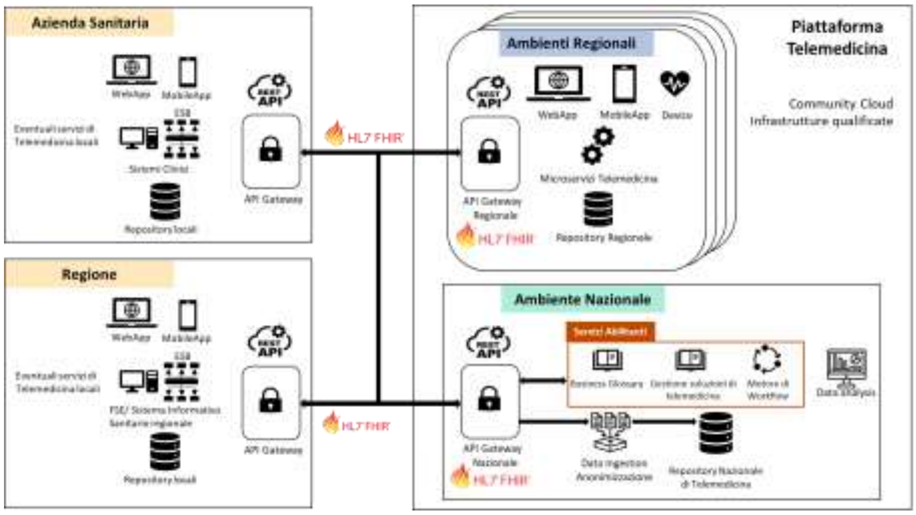

Figure 1 - Digital Health national platform block diagram

2 Devices basket

The activation of the national telemedicine platform enables interoperability with the medical systems and devices used by healthcare companies in the Italian regions [1]. However, there are critical issues related to the heterogeneity of these systems in terms of technology and operating methods. Unlike in other countries, the Italian health service does not have a single contracting station for equipment and medical support services purchase [2]. Each spending center, which coincides with the single local health authority (ASL), is responsible for autonomously proceeding with the market acquisition of necessary instruments, even for the systems that the Ministry of Health has expressed a favorable preventive opinion about [3]. This has led to the use of heterogeneous technological devices, which can make integration on a unitary telemedicine platform extremely difficult. A telemedicine system may require the performance of several functions, such as the measurement of numerous vital parameters and the completion of inter-therapeutic medical interventions at home [4, 5]. This involves the use of various instruments, which may be technologically incompatible with each other or functionally redundant in joint use [6]. Therefore, it is necessary to define a set of appliable devices, called a "basket," for a specific therapeutic protocol. The device choice is up to the specialist doctor who follows the patient, but it may be appropriate to predefine the possible baskets based on axiomatic design. Starting from the user requirements required by healthcare professionals, it is possible to identify the functional requirements to be met [8]. The definition of the functional requirements allows the construction of a set of device baskets necessary to activate a specific health protocol on the telemedicine platform using axiomatic design. The axiom of independence guarantees the logical coherence of the use of the devices in joint form, while the axiom of information allows the selection of the least complex basket [9]. Regarding the evaluation of system complexity, authors propose a reformulation of the information axiom that extends the evaluation of the complexity of a system beyond the evaluation of the functional requirements [10, 11]. Authors suggest that the non-functional elements of a system should also be considered in the overall assessment. Functional requirements represent what the system must do, and all design methodologies are based on a detailed analysis of the systems functional requirements to be implemented [8]. However, there is no rigorous evaluation mechanism for non-functional elements in the design process [10]. To overcome this limitation, authors have placed emphasis on the opportunity to integrate non-functional elements characterizing the system to be designed into a formal process [11]. In this study, authors classify the non-functional elements of a system according to what is defined in the field of software engineering [14, 15]. The aim is to highlight that the non-functional elements of a system themselves do not constitute a single set of characteristics, but in order to better estimate the complexity of a basket, it is necessary to categorize these elements into homogeneous groups.

Therefore, by analogy with software systems, it will be possible to introduce the following classification of the non-functional elements that can characterize a system:

• Non-functional requirements (NFR);

• Project requirements and constraints (PRC).

Non-functional requirements represent specific properties associated with the system. They can be divided into three further subcategories [14, 15]:

• Quality Requirements (QRs). Represent the quality characteristics of the device (Performance, Reliability, Safety, Maintainability, Functional suitability, …);

• System Environment Requirements (SER). Describe the operating context of the system in terms of number and type of users, type of application environment and access methods.

• Technical Requirements (TR). Describe the technologies and technical standards, to which the device must refer.

• Process Domain (Usability, Compatibility and Portability)

Project Requirements and Constraints (PRC) refer to requirements and constraints that do not directly affect the operational management of the system [15]. They pertain to activities such as coordination, training, and the expertise level of personnel using the equipment. Conceptually, the selection process for the proposed robust basket of devices involves integrating non-functional system elements into axiomatic design, as shown in **Figure 2**.

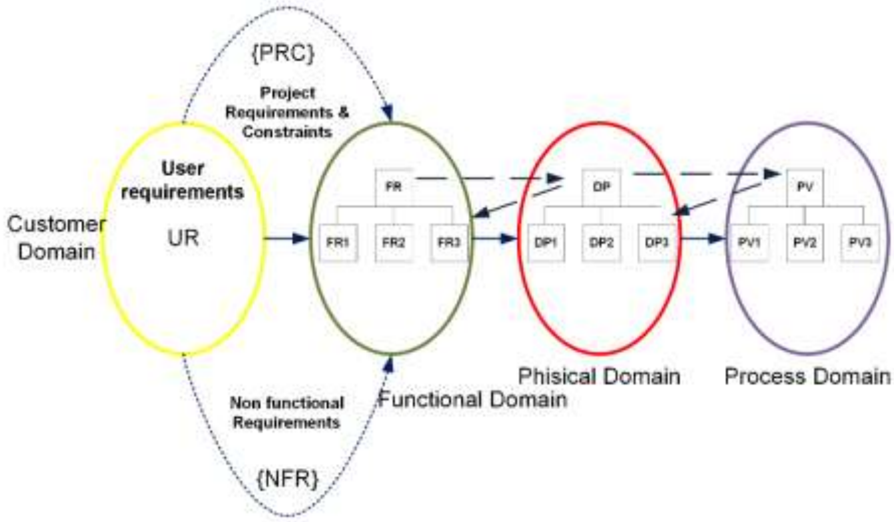

Figure 2 - General Block Diagram forn an AD based method for robust devices basket selection

3 Medical devices basket complexity evaluation as an information axiom extension

The AD standard approach to evaluating system complexity considers only the functional requirements [11, 12, 13]. Essentially, it aims to identify the design solution that satisfies the same functional requirements with the least amount of information content [16]. However, in this study, the authors suggest a new definition of system complexity that takes into account non-functional aspects of basket valuation. To achieve this, they propose reformulating the information axiom, as illustrated in **Figure 3**.

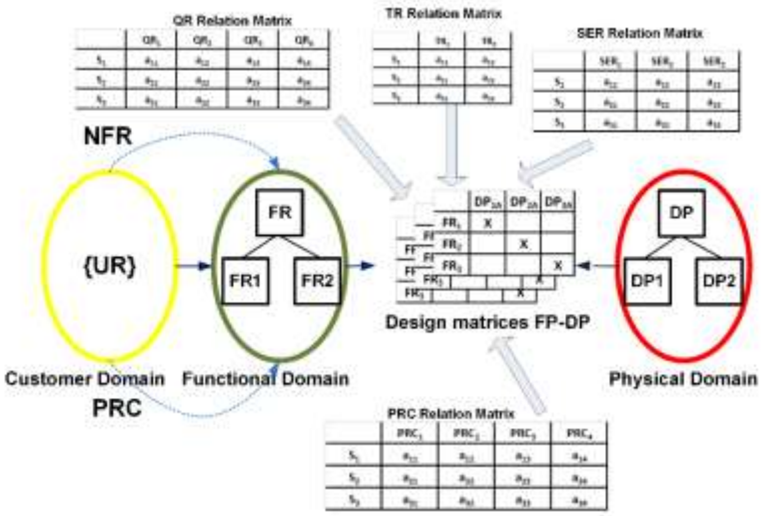

Figure 3 - Information axiom redefinition based on the system non-functional element's introduction

This generalization involves the assessment of admissible sets of medical devices, denoted as "Baskets" (B), which satisfy the independence axiom, across different categories of non-functional elements in the system. This can be achieved by constructing a specific relationship matrix for each of these categories (as shown in Table 1), where the admissible baskets are listed along the rows and the non-functional elements, which serve as evaluation criteria, are listed along the columns. The elements (a_{ij}) of the matrix indicate the impact of the j-th non-functional element on the corresponding basket B_i.

Table 1 - Relation Matrix

	NFR1	NFR2	NFR3	NFR4
$\mathbf{B_1}$	$\mathbf{a_{11}}$	$\mathbf{a_{12}}$	$\mathbf{a_{13}}$	$\mathbf{a_{14}}$
$\mathbf{B_2}$	$\mathbf{a_{21}}$	$\mathbf{a_{22}}$	$\mathbf{a_{23}}$	$\mathbf{a_{24}}$
$\mathbf{B_3}$	$\mathbf{a_{31}}$	$\mathbf{a_{32}}$	$\mathbf{a_{33}}$	$\mathbf{a_{34}}$

From a conceptual standpoint, the creation of relation matrices does not completely resolve the issue [10, 11]. The relationship matrices, as currently formulated, can present uncertain situations where it is not possible to select a unique basket. Additionally, the problem of determining the specific weight or coefficient of each non-functional element of the relation matrix persists [10]. This evaluation involves assigning equal importance to each non-functional element in the most appropriate basket selection of the medical protocol. However, this assumption of equivalence is unrealistic. To address these limitations, it is possible to use a particular type of multi-criteria evaluation, formulated based on subjective value judgments that healthcare professionals can assign to device baskets, identified through the axiom of independence [10, 11]. This type of evaluation allows for the creation of a second table, called a comparison table (Table 2), which assigns weights to the evaluation elements present in a relationship table (Table 1).

Table 2- Comparison Matrix

	NFR_1	**NFR_2**	**NFR_3**	**NFR_4**
	(W_{QR1})	**(W_{QR2})**	**(W_{QR3})**	**(W_{QR4})**
B_1	a_{11}	a_{12}	a_{13}	a_{14}
B_2	a_{21}	a_{22}	a_{23}	a_{24}
B_3	a_{31}	a_{32}	a_{33}	a_{34}

This new matrix will no longer present indeterminacy situations because the impact of each non-functional element is weighted by a specific weight. At this point, the problem becomes determining the weighting coefficients to be attributed to the selection criteria. For this purpose, it is possible to use the information entropy concept, as reported by Pourabbas et al. [10]. This concept provides the analytical tools to determine, based on the value judgments a_{ij} distributions, reported in the matrix in **Table 1**, an estimate of the coefficients W_j [17], where $0< W_j <1$ [12]. The value of W_j will be greater the more the judgments distribution attributed to the baskets constituting the comparison matrix will present strongly discordant evaluations with respect to the j-th non-functional element impact. This implies that the j-th non-functional element carries greater weight than the others do. Conversely, value judgment distributions with low variability will result in low evaluation coefficients, i.e. closer to 0. Information entropy is defined by Shannon [18], and in this context provides a tool for evaluating the variability of value judgments [19]. The methodology can be applied by a team of specialists (professional medical personnel), following a set of precise rules. These rules are necessary to avoid situations of cognitive bias, which can arise when evaluations are based on subjective value judgments. Tversky and Kahneman [20] demonstrated in the field of cognitive psychology that even expert professionals may be susceptible to distorting phenomena when making value judgments. The human mind can assign logically coherent judgments only when two alternatives are compared [21]. In light of this cognitive evidence, Saaty [22] introduced the analytic hierarchy process (AHP) methodology, according to which the value judgments that specialist physicians attribute must be formulated as comparisons between only two baskets at a time. This rule involves redefining comparison matrices in terms of comparing baskets for each non-functional item to be evaluated.

Table 3 represents an example of a comparison matrix according to the AHP approach rules. In this case, the comparison between the same baskets B_i gives the value 1. Instead, if the comparison between the baskets B_i and B_j is given the value a_{ij}, the comparison between B_j and B_j is given the value $1/a_{ij}$. These rules of value judgments attribution make it possible to minimize the cognitive bias phenomenon.

Table 3 - Comparison Matrix for solution alternate for any specific non-functional requirement [22]

QRs	B_1	B_2	B_3	B_4
B_1	1	a_{12}	a_{13}	a_{14}
B_2	$1/a_{12}$	1	a_{23}	a_{24}
B_3	$1/a_{13}$	$1/a_{23}$	1	a_{34}
B_4	$1/a_{14}$	$1/a_{24}$	$1/a_{34}$	1

Furthermore, these judgments must be made on a specific scale of values base (**Table 4**) [11, 22]. This also makes it possible to provide a measure classification that can be associated with the comparison between different baskets.

Table 4 - Evaluation score matrix

Values	S_i vs. S_j level of importance
1	i and j have same importance
3	i moderately more important j
5	i more important than j
2, 4	Intermediate importance levels

4 Robust basket selection

The rules introduced in the previous paragraph allow selecting the robust basket of medical devices based on the estimate of the weighting coefficients associated with the non-functional elements' characteristic of the specific health protocol. These weighting coefficients are estimated considering, for each non-functional evaluation element, the relative comparison matrix (**Table 3**), on which an information entropy generalization is applied.

The information entropy H(x) of a discrete probability distribution p(x) is a positive function defined according to the following formula [18]:

$$H(x) = -\sum_x^X p(x) log p(x) \text{ (eq. 1)}$$

Where X represent a set of instances x.

In order to apply eq. 1 to a comparison matrix (**Table 3**) it is necessary to proceed with the matrix normalization [10]. This operation is performed by replacing in the matrix of **Table 3**, the evaluation judgments a_{ij}, as defined by the expert evaluators, by the corresponding normalized elements A_{ij}, obtainable as follows:

$$A_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^4 a_{ij}^2}} \text{ (eq. 2)}$$

So, from the comparison matrix **Table 3**, it is obtained the normalized comparison matrix A. Based on this new matrix, eq. 1 become:

$$H(A_i) = \sum_{j=1}^4 H(A_{ij}) = -\sum_{j=1}^4 A_{ij} log A_{ij} = W_i^{NFE_s} \text{(eq.3)}$$

Where $W_i^{NFE_s}$ represents the weighting coefficient associated with the i-th row of the comparison matrix relating to the non-functional elementNFE_s.

Repeating the calculation for each i-th row of the normalized comparison matrix A, the following vector of weighting coefficients [10] is obtained:

$$W^{NFE_s} = \begin{bmatrix} W_1^{NFE_s} \\ W_2^{NFE_s} \\ W_3^{NFE_s} \\ W_3^{NFE_s} \end{bmatrix} \text{(eq.4)}$$

These weighting coefficients can be put together in an overall comparison matrix, such as the one shown in **Table 5**. It brings together all the weighting coefficients calculated for the non-functional elements considered.

Table 5 - Weighting matrix of non-functional items

	NFE_1	*NFE_2*	-	*NFE_m*
B_1	$W_1^{NFE_1}$	$W_1^{NFE_2}$	-	$W_1^{NFE_m}$
B_2	$W_2^{NFE_1}$	$W_2^{NFE_2}$	-	$W_2^{NFE_m}$
-	-	-	-	-
B_n	$W_n^{NFE_1}$	$W_n^{NFE_n}$	-	$W_n^{NFE_m}$

he B_{i*} robust basket will be the solution with the highest $W_i^{NFE_m}$ parameters sum within the B set of admissible This algorithm enables the definition of a ranking among n allowable baskets (B_i) while considering the non-functional elements specified in the operational context. However, as illustrated in **Figure 2**, non-functional elements can pertain to various categories, and therefore, evaluating them simultaneously is inappropriate. To address this, a specific extension of the aforementioned method can be utilized, wherein structured hierarchical evaluation is employed. The Analytic Hierarchy Process (AHP) method can support this approach, and it enables the use of the entropy criterion through a decision tree (refer to [22, 23]). By evaluating the weighting coefficients (W_j) associated with sub-criteria, it is possible to perform successive aggregations, as shown in **Figure 4**. This criterion facilitates the determination of weighting coefficients for various sub-criteria (QR, TR, SER) and allows the creation of Non-Functional Requirement (NFR) comparison matrices that encompass the three functional requirement categories. Additionally, it is possible to combine NFRs and Performance-Related Characteristics (PRCs) to generate an overall comparison matrix that enables the selection of the robust Si* solution based on a hierarchical application of information entropy. This generalization enables the separation of elements with distinct characteristics into homogeneous subsets to achieve a more accurate evaluation (refer to [23]).

$$S_{i*} = Max_{i=1}^{n}\left(\sum_{j=1}^{m} W_i^{NFE_m}\right) \text{ (eq.5)}$$

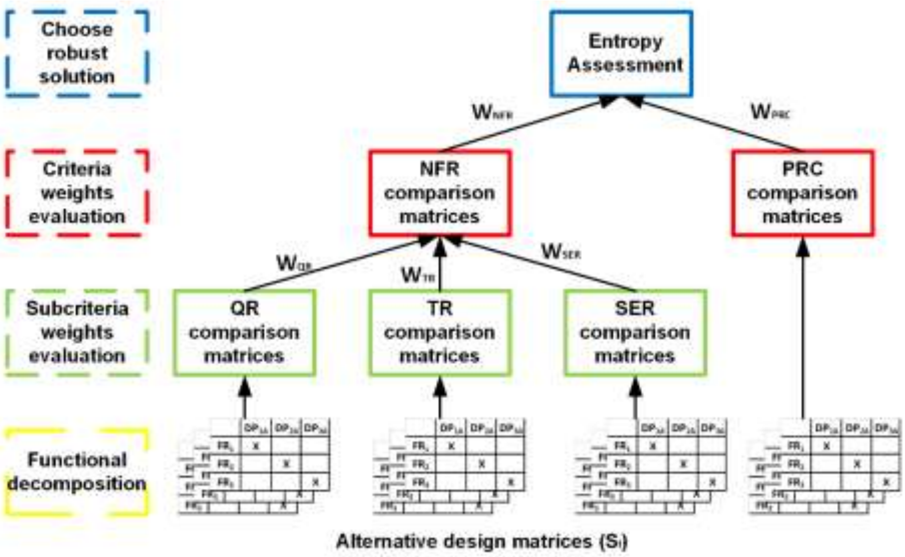

Figure 4 - Information entropy method to evaluate a robust basket. A method generalization

5 Conclusions

A national platform for delivering microservices in telemedicine represents a significant opportunity to enhance the Italian healthcare system. However, it also presents considerable challenges to local health companies, in terms of not only transitioning to digital services but also regarding interoperability, usability, and safety. The proposed approach offers several advantages in this context. Firstly, the use of axiomatic design as a tool for basket composition enables the identification of device collections that meet all functional requirements for both patients and healthcare professionals for specific healthcare protocols. Axiomatic design helps avoid combinations of technological or functional incompatibilities and reduces the duplication of redundant functions. This is particularly relevant given the technological heterogeneity of devices used in Italian healthcare companies, which may cause incompatibilities during technological integration with the telemedicine platform. To address this issue, the proposed approach involves a reformulation of the information axiom to redefine the concept of complexity using a wider set of criteria that include non-functional characteristics of devices. These criteria may include the level of interoperability, usability, portability, security, and confidentiality of processed data. The concept of information entropy is used to estimate the relevance of these non-functional elements based on value judgments attributed to the adoption of specific device baskets by teams of specialist doctors. However, selecting these instruments is the responsibility of the specialists, who may find it challenging to formulate comprehensive judgments. In these cases, subjective judgments are formulated through a comparison of two alternative solutions against a well-defined scale of values, reducing the possibility of cognitive bias. The information axiom reformulation can also be adopted to include economic aspects in the decision-making process. In this case, the complexity of the system will have an economic dimension, which is also relevant given the needs of spending review.

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