Chapter

Conceptual Design Evaluation of Mechatronic Systems

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Abstract

The definition of the conceptual design phase has been expressed in many different phrasings, but all of them lead to the same conclusion. The conceptual design phase is of the highest importance during the design process, due to the fact that many crucial decisions concerning the progress of the design need to be taken with very little to none information and knowledge about the design object. This implies to very high uncertainty about the effects that these decisions will have later on. During the conceptual design of a mechatronic system, the system to be designed is modeled, and several solutions (alternatives) to the design problem are generated and evaluated so that the most fitting one to the design specifications and requirements is chosen. The purpose of this chapter is to mention some of the most widely used methods of system modeling, mainly through hierarchical representations of their subsystems, and also to present a method for the generation and evaluation of the design alternatives.

Keywords: conceptual design, mechatronic design, hierarchical modeling, concept evaluation, mechatronic abilities, Choquet integral, criterion interactions

1. Introduction

The current mechatronic systems acquire very advanced capabilities based on the evolution of the mechatronics enabling technologies and the mechatronic design methodology. The enhanced intelligence of the mechatronic systems and the increased complexity are identified; however, these changes drive to completely new characteristics and capabilities of mechatronic systems supporting the new generation of production systems, e.g., these devices evolved from the simple monitoring to self-optimizing their performance. On top of that, mechatronics enhanced the application domains from manufacturing to biomechatronics and micromechatronics.

The development of mechatronic products and systems requires concurrent, multidisciplinary, and integrated design approaches. This chapter deals with methods and models used during the mechatronic design and more specifically with the design evaluation. A method for concept generation and evaluation is presented. The criteria used as well as the mathematical foundations of the method will be presented and analyzed. More specifically, the mechatronic criteria based on the mechatronic abilities as well as their scoring will be described using a systematic approach. Aggregation of the new criteria will be performed using a nonlinear fuzzy integral. The use of the mechatronic design index in a chosen application task will be presented.

The next section of this chapter is a two-part state of the art. First, the conceptual design of mechatronic systems and different techniques and approaches for the system modeling and representation during this phase are discussed. Later, the state of the art concerning concept evaluation methodologies and indexes is presented. A method for concept evaluation is proposed in Section 3 of the chapter. In the final section, an exemplary case study of the conceptual design phase of a mechatronic object is presented and discussed in the Conclusions section.

2. State of the art

2.1 System modeling and hierarchical representations

Conceptual model creation of a mechatronic object to be designed is the actual task for industrial production systems that usually operate with modern CAD/CAM systems [1–4]. According to [1], in the object life cycle, the conceptual design is made just before the phase of creating the detailed design, when the object's concrete mathematical model is created and numeric calculations are realized.

Nowadays, there are many definitions of conceptual design and corresponding methods and models that are used at the conceptual design phase analyzed in [5]. An opinion given by Hudspeth [5] is that conceptual design is more about what a product might be or do and how it might meet the expectations of the manufacturer and the customer. M. J. French defines conceptual design as the phase of the design process when the statement of the problem and generation of a broad solution to it in the form of schemes is performed [6].

The US Department of Transportation's FLH Project Development and Design Manual [7] states that conceptual studies (CS) are typically initiated as needed to support the design planning and programming process. The CS phase identifies, defines, and considers sufficient courses of action (i.e., engineering concepts) to address the design needs and deficiencies initially identified during the planning process. This phase advances a project proposed in the program to a point when it is sufficiently described, defined, and scoped to enable the preliminary design and technical engineering activities to begin. The CS studies and preliminary design phases are performed in conjunction and concurrently with the environmental process, which evaluates environmental impacts of the engineering proposals resulting from the conceptual studies and preliminary design phases.

Functional modeling technology was researched and applied to represent concept design knowledge by [8, 9] presented a function-behavior-structure (FBS) ontology representation process for concept design in different domains and emphasized the reasoning mechanism with the FBS ontology for knowledge representation.

Borgo et al. [10] proposed an ontological characterization of artifact behavior and function to capture the informal meanings of these concepts in the engineering practice and characterize them as part of a foundational ontology. The function-cell-behavior-structure (FCBS) model to better comprehend representation and reuse of design knowledge in conceptual design was proposed by Gu [11]. A hierarchical two-layer concept is given here, i.e., two knowledge-representing layers—the principle layer and the physical layer—are presented in the FCBS model. The principle layer is utilized here to represent the principle knowledge. Case modeling is employed in the physical layer to integrate the structural information and behavioral performances of the existing devices that apply the design principles represented by the functional knowledge cells (FKCs).

A formal definition of the concept design and a conceptual model linking concepts related to design projects are proposed by Ralph and Wand [12]. Their definition of design incorporates seven elements: agent, object, environment, goals, primitives, requirements, and constraints. The design project conceptual model is based, here, on the view that projects are temporal trajectories of work systems that include human agents who work to design systems for stakeholders and use resources and tools to accomplish this task. Ralph and Wand [12] demonstrate how these two conceptualizations can be useful by showing that (1) the definition of design can be used to classify design knowledge and (2) the conceptual model can be used to classify design approaches.

An approach for using hierarchical models in the design of mechatronic systems is presented by Hehenberger in [13]. To master the mechatronic design approach, a hierarchical design process is proposed. The models cover the different views on a system as well as the different degrees of detailing. The utilization and proper combination of solution principles from different domains of mechatronics allow an extended variety and quality of principal solutions, where hierarchical models serve as very important tools for complex design tasks. Analysis of different mechatronic design concepts is also conducted in the work. The approach is demonstrated by studying the activities during the design process of synchronous machines.

Another approach used in mechatronic design is knowledge-based engineering (KBE) described by Sobieszczanski-Sobieski in [14]. The main structures for extended KBE application are design process and design models. The models contain specific aspects such as product structure as a whole and its fragments, engineering calculations, and analysis with ability of integration with external systems, design requirements, and decision-making processes. This object-oriented approach makes it possible to speed up the process of generating the source code of design models from the extended KBE and supports multidisciplinary design optimization. Knowledge-based hybrid intelligent systems, namely, imperialist competitive algorithm, artificial neural networks, genetic algorithms, and particle swarm optimization, are also used in tunnel design and construction processes and described in [15].

Mathematical models used in design and modeling of mechanical structures of mechatronic systems are described in [16]. The examples of car suspension system modeling were presented in this work. The approach of interactive design and production evaluating of a manufacturing cell is described in [17].

The use of hierarchical system (HS) formal construction and HS coordination technology in conceptual design of mechatronic objects is proposed and described by Miatliuk [18].

2.2 Concept evaluation and generation

The mechatronic design quotient (MDQ) [19–21] was proposed as a multicriterion measure for assisting decision-making in mechatronic design. In MDQ seven criteria were incorporated: meeting task requirements, reliability, intelligence, matching, control friendliness, efficiency, and cost. These criteria are aggregated by means of the Choquet Integral—a nonlinear fuzzy integral that can be used for assisting decision-making with interactive criteria [22]. Guidelines for the concept evaluation using these criteria were presented in [21], where four alternatives of an industrial fish cutting machine were evaluated using a hierarchical classification of the aforementioned criteria and the Choquet integral as the aggregator.

The mechatronic multicriteria profile (MMP) [23] includes five main criteria (machine intelligence quotient, reliability, complexity, flexibility, and cost of manufacture and production) for the mechatronic concept evaluation. The MMP criteria are defined in such a way that the assessment of the alternatives with respect to each criterion results from measurable sizes and does not depend entirely on the designer's judgment and experience. In [23], the proposed method is applied to the conceptual design of a visual servoing system for a 6-DOF robotic manipulator, and the Choquet nonlinear fuzzy integral is used for the aggregation of the criteria. Three different aggregation techniques, the Choquet integral, the Sugeno integral, and a fuzzy-based neural network, were tested and compared for the design evaluation of a quadrotor mechatronic system [24].

The mechatronic index vector (MIV) introduced in [2] consists of three criteria, intelligence, flexibility, and complexity. The attributes of every criterion are analyzed and formulated. The intelligence level of a system is determined by its control functions, and the structure for information processing of mechatronic systems is used to model intelligence. A technique to measure the flexibility of manufacturing systems was used for the estimation of the flexibility of a mechatronic product. The various types of flexibility were classified in three main categories, namely, product flexibility, operation flexibility, and capacity flexibility. The complexity was modeled using seven elements. Various models for aggregating the criteria were proposed and compared including t-norms, averaging operators [2], and the discrete Choquet integral [25].

Ferreira [26] proposed a decision support tool based on a neural network to provide suggestions for early design decisions based on previous solutions. In the same manner, the mechatronic design indicator (MDI) was proposed [27] as a performance indicator based on a neuronal network of radial basis functions.

In [28], Moulianitis proposed a new mechatronic index for the evaluation of alternatives. The proposed criteria that make up the mechatronic index were mainly extracted from the collective knowledge presented in the multi annual roadmap (MAR) for robotics in Europe [29] and adapted by considering the recent advancements in mechatronics. The discrete Choquet integral is used for the aggregation of the evaluation scores, while also taking into account the correlations between criteria. The criteria and the aggregation method of the mechatronic index are presented in detail in the following sections.

In recent years, some research has been focused in the automated generation of system architecture concepts for mechatronic design problems. In [30], an automated generation and evaluation method for feasible and ranked physical architectures is proposed. First, the components that can realize specified system functions are identified and combined with the use of a unified knowledge model and dynamic programming methods. Then, the criteria are realized, and the system architectures are evaluated based on the technique for order preference by similarity to an ideal solution (TOPSIS).

An integrated principle solution synthesis method which achieves the automated synthesis of multidisciplinary principle solutions but also solves the undesired physical conflicts among synthesized solutions was proposed in [31].

In [32], a model-based research approach for an integrated conceptual design evaluation of mechatronic systems using SysML software is proposed and applied to the design of a two-wheel differential drive robot to find the optimal combination of component alternatives for specific evaluation goals.

3. Concept evaluation in mechatronic design

In this section, the necessary steps for concept evaluation are presented and described. The process is described in terms of a flowchart in **Figure 1**.

The definition of the design specifications and requirements is a perquisite for a more complete evaluation. The designer can also capitalize on a well-defined set of

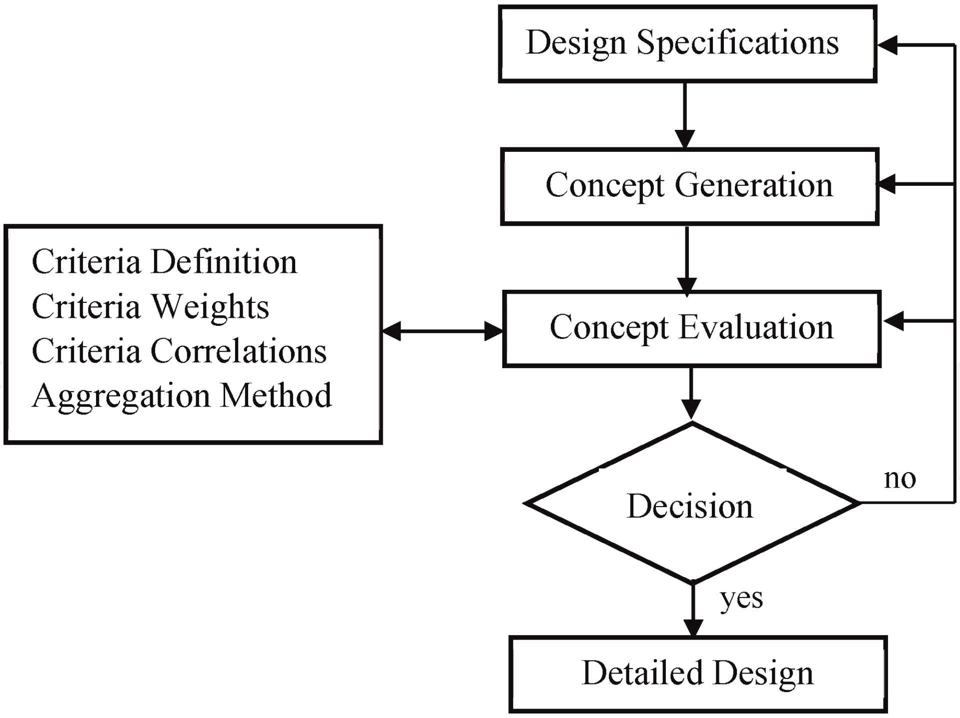

Figure 1.
The proposed evaluation process during the conceptual design phase.

requirements and specifications in order to generate functional concepts that will later be evaluated. In order for the evaluation to take place, four steps are necessary. The criteria that are to be used for the evaluation of the alternatives must be chosen and defined. Then, the weights (importance) of the said criteria must be decided, as well as the interactions between them. The design alternatives are then evaluated with respect to each criterion, and those scores are aggregated using a discrete Choquet integral in order for the final scoring values to be derived. The alternative with the highest score is considered to be the most suitable to the design problem, given the specific requirements and other design environment characteristics (design team experience, knowledge, etc.). At this point, the designer has the choice to select the alternative that will be further developed during the detailed design phase or to review some of the previous step and reevaluate the design alternatives. The steps presented in **Figure 1** are presented in more detail in the following paragraphs. The final section of this chapter is an exemplary case study where the proposed evaluation method is used for the evaluation of a mechatronic system.

3.1 Design specifications

In the early stage of defining the mechatronic system/product to be designed, the engineering specifications and constraints are determined. The quality function deployment (QFD) is a well-known and widely used method for deriving the design specifications and constraints by realizing customers' needs and requirements. In [33], the classification of design specifications to demands and wishes is proposed, and, by extension, the further grading of wishes is based on their importance over the design process. The determination and the recording of design specifications are of great importance to the concept generation and evaluation processes. During the concept generation process, design specifications and constraints can help the designer to easily recognize any unfeasible concepts that will not satisfy the minimum requirements, while during the concept evaluation process, the designer can consult the list of customer requirements and design specifications for the evaluation criterion selection and the determination of their weights.

3.2 Concept generation

Concept generation is the process where possible solutions to the design problem are realized based on design specifications and functions that the system/product must accomplish. In order for a generated concept to be considered a feasible solution to the design problem, the two following conditions must be satisfied: (a) the concept meets at least the minimum design specifications, and (b) it includes the necessary software and hardware components [28]. Concepts can be represented in different ways, such as sketches or flow diagrams, function hierarchies, textual notes, or table representations. However, regardless of which way a concept is represented, enough detail must be developed to model performance so that the functionality of the idea can be ensured [1]. The quality and the thoroughness of the generated alternatives mainly depend on the available information and knowledge about the design problem at that early stage of the process and the experience of the design team.

3.3 Concept evaluation

In the concept evaluation stage, the concepts that have been generated are being evaluated with respect to some criteria. The performance of each alternative with respect to each criterion is rated, and these scores are aggregated with a specified aggregation function. The purpose of the evaluation is to support the decision-making process of the designer and help him/her to choose the best concept for further analysis in the detail design stage. In this section, the basic ideas behind each step of the process will be described, and different ways of implementing them will be mentioned. More emphasis will be placed on describing the foundations and methods (criterion definition, aggregation function, correlations between criteria) to be applied in the exemplary case study that follows in the next section.

3.4 Criterion definition

A criterion can be thought of as a measure of performance for an alternative [34]. As we saw earlier in the state of the art section, more than a few criteria and combinations of those criteria have been proposed for the evaluation of mechatronic concepts. The type and number of criteria to be used are up to the designer and the stakeholders that take part in the design process. The selection of criteria could depend on the designer's experience and personal judgment; the available information and knowledge about the design problem; the alternatives and the abstraction level of their description, design specifications, and customer requirements; and whether the designer wants to incorporate the interactions among the criteria in the decision-making process.

For the purposes of this chapter, the mechatronic abilities proposed by Moulianitis in [28] as criteria for the evaluation of mechatronic systems will be used in the exemplary case study. The criteria are based on the collective knowledge presented in the Multi Annual Roadmap (MAR) for Robotics in Europe [29]. The mechatronic abilities found in [28] are the following:

- Adaptability
- Configurability

- Decisional autonomy
- Dependability
- Interaction ability
- Motion ability
- Perception ability

Abilities provide a basis for setting performance metrics and for application providers to specify desired levels of system performance [29]. These ability levels are adapted to mechatronic criteria, and a scoring scale for concept evaluation with respect to these criteria is presented [28]. Different scaling types for scoring and evaluation of criteria have been proposed, and the dispute concerning the superiority among them has been discussed in [35]. The way the criteria are mapped to scoring methods affects the evaluation results, meaning that a suitable mapping could lead to more realistic results. However, this work is outside the scope of this chapter and is left for future work.

For the scoring of alternatives, it is assumed that the progression of the levels advances the characteristics of the system linearly, so a linear interpolation is used to map each level to a score. The criteria are scaled in the same universe of discourse, with the lowest possible value being equal to zero and the highest possible equal to one. The scores of the intermediate levels are assigned linearly between zero and one. In the following, the scaling of the criteria according to [28], as well as short descriptions of the criteria, is provided.

3.4.1 Adaptability

Fricke [36] defined adaptability as the ability of a system to adapt in order to deliver intended function ability under varying conditions by changing the values of the design parameters either actively (online) or passively (off-line). In [29], adaptability is defined as the ability of the system to adapt itself to different work scenarios and different environments and conditions. Adaptability is often mixed with configurability and decisional autonomy but is differentiated by configurability in the sense that adaptation is mostly devoted to the parameter change rather than to the structure change. The difference between autonomous decision and adaptation is that adaptation takes place over time based on an accumulation of experience, while decisional autonomy is a result of environmental perception by means of sensors and cognitive mechanisms.

Adaptability can be broken down to five ability levels, starting from Level 0 when the system has no ability to adapt and reaching up to Level 4 when the process of adaptation is carried out by multiple agents. In the three intermediate levels, the system behavior is self-evaluated, and the need for parameter adaptation is recognized (Level 1), and in addition, individual parameters can be altered based on local performance assessment (Level 3), and in Level 4 the adaptation concerns multiple parameter changes. The levels of adaptability and the scaling for the scoring of each level are presented in **Table 1**.

3.4.2 Configurability

Configurability is the ability of a system to alter its configuration to perform different tasks. As it is stated in [29], configurability must be carefully distinguished

Adaptability level	Normalized score
0	0
1	0.25
2	0.5
3	0.75
4	1

Table 1.
Levels and scaling for adaptability.

from adaptability and decisional autonomy which relate to how a robot system alters its responses (adaptability) and how it changes its behavior as it performs an operating cycle. At the highest level (Level 4) of configurability, the system is able to sense changes in its environment's conditions that are not pre-programmed and alter its configuration in response to those changes. At the lowest levels, the system has a single and non-alterable configuration (Level 0), and at Level 1 the user is responsible for the definition of the system configuration at the beginning of each cycle of operations. As we go up to Level 3, the system can alter its configuration autonomously from a predetermined set of alternative built-in configurations, and in Level 4 the system is able to alter its configuration in response to changing conditions that are not pre-programmed or predetermined. The score scaling for each configurability level is shown in **Table 2**.

3.4.3 Decisional autonomy

A feature of many mechatronic systems is the devolution of functional responsibility to the system, freeing the operator or user to pay attention on the higher-level functions associated with the deployment and applicability of the system [37]. In order to enhance the decisional autonomy of a system, it should be equipped with heuristics, machine learning capabilities, logic tools, etc. The same as before, the leveling starts from Level 0 for systems with no ability to take decisions, and it goes up as the system enhances its ability to take decisions. At first, the system is fully dependent on user decisions (Level 1), the system makes decisions to choose its behavior from a predefined set of alternatives based on basic sensing and user inputs (Level 2), and at Level 3 the system is able to process the inputs from the user and the sensing unit and makes decisions continuously, while in Level 4 moment-to-moment decisions about the environment are taken. Level 5 introduces an internal model of the environment to the system in order to support the system's decision-making process, and when in Level 6, the sequence of predefined subtasks is decided in a way, so it accomplishes a higher-level task. Level 7 means that the system can adapt its behavior to accommodate task constraints, and Level 8

Configurability level	Normalized score
0	0
1	0.25
2	0.5
3	0.75
4	1

Table 2.
Levels and scaling for configurability.

translates to the alteration of the strategy as the system gathers new information and knowledge about the environment. In the two higher levels, decisions about actions are altered within the time frame of dynamic events that occur inside the environment (Level 9), and in Level 10, system compensation in real-time events is enabled by the alteration of the tasks themselves. The levels and the corresponding scores are presented in **Table 3**.

3.4.4 Dependability

Dependability of mechatronic units is defined as the qualitative and quantitative assessment of the degree of performance, reliability, and safety taking into consideration all relevant influencing factors [38]. The higher the level of dependability of a system, the more reliable this system is. Seven levels of dependability are defined as follows. At Level 0, there is no system ability to predict any failures. At Level 1, dependability is measured only by estimations of the mean time between failures, and the system has no real ability to detect or prevent those failures. At Level 2, the system has the ability to diagnose a failure and enter safe mode operation, while at Level 3 the system is able to diagnose a number of failures and recover from a proportion of them. If the system has the added ability to predict the consequences to its tasks caused by the diagnosed failures, then it has reached Level 4. At Level 5, the system can communicate its failures to other systems in order to rearrange the aggregate sequence of tasks and keep its mission dependable, and as we reach Level 6, the system is able to predict a failure and act to prevent it. Dependability levels and scores are presented in **Table 4**.

3.4.5 Interaction ability

It is the ability of a system to interact physically, cognitively, and socially either with users, operators, or other systems around it [29]. In the concept of human adaptive mechatronics (HAM) [39], the goal is to design a mechatronic system that includes the user in the control loop and modifies the functions and the structure of user-machine interface to improve the human's operational skills. Interactivity is considered in most of the modern mechatronic systems to facilitate either the

Decisional autonomy level	Normalized score
0	0
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1

Table 3.
Levels and scaling for decisional autonomy.

Dependability level	Normalized score
0	0
1	0.17
2	0.33
3	0.5
4	0.67
5	0.83
6	1

Table 4.
Levels and scaling for dependability.

operation or the maintenance and repair. Six levels were used for the modeling of interaction ability. Level 0 entails that no ability for interaction exists. The lowest level where human-system interactions are present is Level 1, where the operation of the system can be interrupted at any time by the user. When human-machine interaction is possible even if the user and the system are isolated, we are at Level 2, and if the system's workspace is divided into safe and unsafe zone for human interaction, then Level 3 of interaction ability is reached. At Level 4, human-system synergy is considered, while the system checks for dangerous motions or forces that could be harmful to the human. At the highest level, that is, Level 5, recognition of the conditions under which the system should have a safe mode behavior based on detection of uncertainty is enabled. Interaction ability levels and their scoring are presented in **Table 5**.

3.4.6 Motion ability

In [28], motion ability is considered to categorize the different types of motion control. Open-source 3D printers are systems with Level 1 motion ability, while robotic vacuum cleaners are presenting abilities up to Level 5. Motion ability levels and the scores are presented in **Table 6**. At the lowest level (Level 0), the system presents no motion ability. As we go up to Level 1, the system accomplishes predefined motions in a sequence using open-loop control, while the use of closed-loop control for motion in a predefined manner is considered to be at Level 2 of motion ability. Level 3 offers the ability for constrained position or force options integrated to the motion control, while a reactive motion describes Level 4. Optimization of a set of parameters and planning of its motion based on said optimization translate to Level 5 of motion ability.

Interaction ability level	Normalized score
0	0
1	0.2
2	0.4
3	0.6
4	0.8
5	1

Table 5.
Levels and normalized values for interaction ability [10].

Motion ability level	Normalized score
0	0
1	0.17
2	0.4
3	0.6
4	0.8
5	1

Table 6.
Levels and scores for motion ability [10].

3.4.7 Perception ability

In order for mechatronic systems to be capable of operation in unstructured, dynamic environments, multiple sensors and methods for sensor fusion and environment recognition are integrated into them [40]. The perception ability of a system is associated with its ability to understand and sense its working environment. The leveling of the perception ability extends to eight levels in total. The same with all the previous mechatronic abilities, Level 0 means that there is no ability to perceive data. If critical data are collected using sensors and the behavior of the system is directly altered, then the system is at Level 1 of perception ability. If the collected data are first processed and the behavior of the system is then indirectly altered, we are at Level 2. At Level 3, multiple sensors are being used to create a unified model of the surrounding environment, while at Level 4 system is able to extract features of the environment by sensing only a region of it. Being a Level 5 system goes with the ability to process the sensing data in order to extract information features that help with better environment interpretation. At Level 6 objects are identified using an object model, and at the highest level, Level 7, processed data are used in order to infer about properties of the environment. Perception ability levels and their scoring are given in **Table 7**.

3.4.8 Criteria weights

Criteria weights express the designer's preference for the importance of each criterion in the assessment of the alternatives. Various methods for assigning weights to criteria have been proposed in the relevant literature [1, 33, 34, 41]. The

Perception ability level	Normalized score
0	0
1	0.14
2	0.29
3	0.43
4	0.57
5	0.71
6	0.86
7	1

Table 7.
Levels and normalized scores for perception ability [10].

most commonly used weight assignment technique for concept evaluation in the mechatronic design process is the direct rating of each criterion weight by the decision-makers (direct rating, point allocation, numerical scale) [1, 41, 42]. The eigenvector method, proposed by Saaty in [43], is a simple method that uses pairwise comparisons and ratings between criteria in order to formulate the weight of each individual criterion. In [34, 41], the reader can find a more in-depth analysis of different weight rating methods and how to choose the most suitable method depending on the decision problem. In the process of assigning values to criteria weights, the design team should make an effort to consider the design specifications and customer requirements and try to reflect them on the assigned values.

3.5 Criteria correlations and aggregation method

Choquet integral is a nonlinear fuzzy integral, which has been proposed and used for the aggregation of interacting criteria [22]. The integral allows for the designer to incorporate interactions into the evaluation process by providing weighting factors (weights) both for the criteria and the correlations between each subset of criteria. Considering the set of criteria $X = \{x_1, x_2, ..., x_n\}$, the concept of a fuzzy measure [44] is defined.

A fuzzy measure on the set X of criteria is a set function $\mu : P(X) \rightarrow [0, 1]$ satisfying the following axioms:

i. $\mu(\varnothing) = 0$ *and* $\mu(X) = 1$

ii. $A \subset B \subset C$ *implies* $\mu(\mathrm{A}) \leq \mu(\mathrm{B})$.

In this context, $\mu(\mathrm{A})$ represents the weight of importance of criterion A [22]. By expressing the weighting factors of each subset of criteria, the interactions between criteria can be taken into account during the aggregation. Four types of interactions between criteria are presented in this chapter. A positive interaction (or correlation) means that a good score in criterion x_i implies a good score in criterion x_j and vice versa, while a negative correlation between interacting criteria means that a good score in criterion x_i implies a bad score in criterion x_j and vice versa. If a criterion has a veto effect on the evaluation process, a bad score in criterion x_i results in a bad global score. A pass effect, on the other hand, implies that a good score in criterion x_i results in a good global score. In **Table 8**, the four types of interactions between criteria and the relations between their weighting factors are presented.

Given the set of criteria X and the fuzzy measure μ, the Choquet integral of a function $f : X \rightarrow [0, 1]$ with respect to μ is defined by [23]

$$C_\mu = C_\mu(f(x_1), ..., f(x_n)) \coloneqq \sum_{i=1}^{n} \left[\left(f\left(x_{(i)}\right) - f\left(x_{(i-1)}\right)\right) \mu\left(\mathrm{A}_{(i)}\right) \right] \tag{1}$$

Interaction	Relation
Positive correlation	$\mu(x_i, x_j) < \mu(x_i) + \mu(x_j)$
Negative correlation	$\mu(x_i, x_j) > \mu(x_i) + \mu(x_j)$
Veto effect	$\mu(T) \approx 0$ *if* $T \subset X - \{x_i\}$
Pass effect	$\mu(T) \approx 1$ *if* $T \subset X, x_i \in T$

Table 8.
Correlations between criteria.

where $(.)_{(i)}$ indicates that the indices have been permuted so that $0 \leq f(x_1) \leq \ldots \leq f(x_n) \leq 1, f(x_{(0)}) = 0$, and $A_{(i)} = [x_{(i)}, \ldots, x_{(n)}]$.

or equally [45]

$$C_\mu = \sum_{i=1}^{n} f(x_{(i)}) [\mu(A_{(i)}) - \mu(A_{(i+1)})] \tag{2}$$

where $(.)_{(i)}$ indicates that the indices have been permuted so that the criteria values are sorted in ascending order, such that $0 \leq f(x_1) \leq \ldots \leq f(x_n) \leq 1$, $A_{(i)} = [x_{(i)}, \ldots, x_{(n)}]$, and $A_{(n+1)} = 0$.

Marichal [45] also proposed an axiomatic characterization of the integral to motivate its use in applications. The expression he ended up with is the Choquet integral in terms of the Mobius representation:

$$C_\mu = \sum_{i \in N} a(i) \bullet f(x_{(i)}) + \sum_{\{i,j\} \subseteq N} a(i,j) \bullet [f(x_{(i)}) \wedge f(x_{(j)})] + \ldots \tag{3}$$

where $a(i) = \mu(i)$ and $a(i,j) = \mu(i,j) - [\mu(i) + \mu(j)]$.

4. Case study: automated BMP system

The proposed method is used for the concept evaluation of an automated biomethane potential (BMP) measurement system. Before the presentation of the evaluation of the system, it should be mentioned that all the scoring values of alternatives, the criteria weights, and the criteria correlation weights were given intuitively by the authors of this chapter. This is not ideal, since the design team should strive for a more analytic and objective approach to the evaluation process. However, the study of the cognitive mechanisms that take place during the evaluation and the consideration of different ways of scoring criteria and criteria weights is left for future work. The purpose of this chapter is to focus more on the general methodology for concept evaluation and not so on its specifics.

Production of biogas from different organic materials is an interesting source of renewable energy. The biomethane potential (BMP) of these materials has to be determined to get insight in design parameters for anaerobic digesters [46]. The test is conducted by placing an active inoculum and a sample of a substrate in a sealed container vessel and measuring the amount of the gas produced [47]. The basic steps followed in a BMP test are:

1. The substrate and the inoculum are placed in the sealed reactor vessel.

2. Stirring (not continuous) and heating (the temperature is held constant in the range 20–90°C, depending on the test mixture) of the test mixture to enhance biogas production. The production of biogas starts at this step and continuous until the end of the experiment.

3. Absorption of CO_2. The biogas is transferred to a reactor vessel containing (liquid) NaOH. This allows for the dissolution of the CO_2 in the NaOH solution, and the remaining gas volume is representative of the CH_4 present in the biogas.

4. Gas flow measurement. The CH_4 is transferred to the flow measurement system. The volume of gas produced in a specific time interval is quantified, usually under the fluid displacement principle.

5. Data analysis and reporting.

An average BMP test can last for more than 30 days, during which the test system must run without disruptions. The BMP test can be done manually, where human interference in 24-h intervals is needed in order for the gas flow measurement to take place. The whole process can also be automated, where no human interaction is needed for the gas flow measurement, and the analysis and representation of the results take place in real time during the experimental process. Two commercial products that automate the BMP test are the AMPTS II by Bioprocess Control Systems [48] and the Biogas Batch Fermentation System by Ritter [49]. The following scheme represents the basic functions that need to be accomplished for the automation of the process. The functions presented in the scheme in **Figure 2** are incorporated in both products (AMPTS II and Biogas Batch Fermentation System).

In **Figures 3** and **4**, the two products are presented in relation to the scheme given in **Figure 2**. They accomplish the same functions but with slightly different components and working principles.

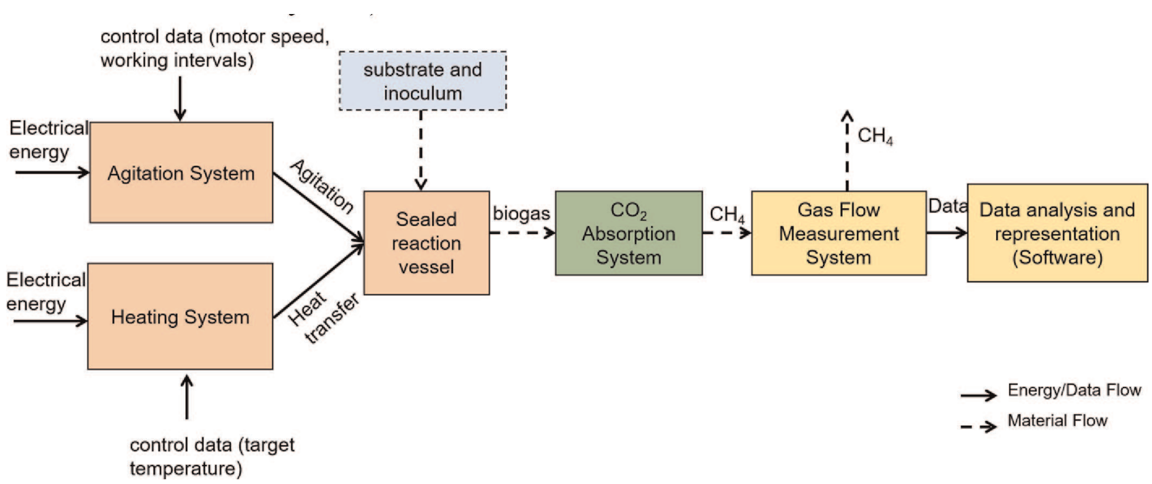

Figure 2.
Subfunctions and flows of material and energy of an automated BMP system.

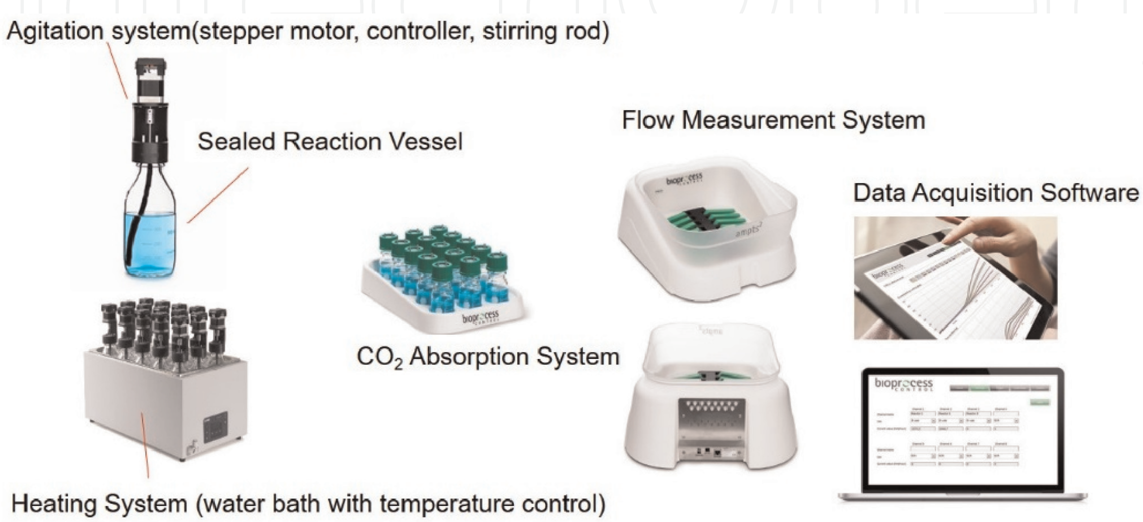

Figure 3.
The AMPTS II system by bioprocess control [48].

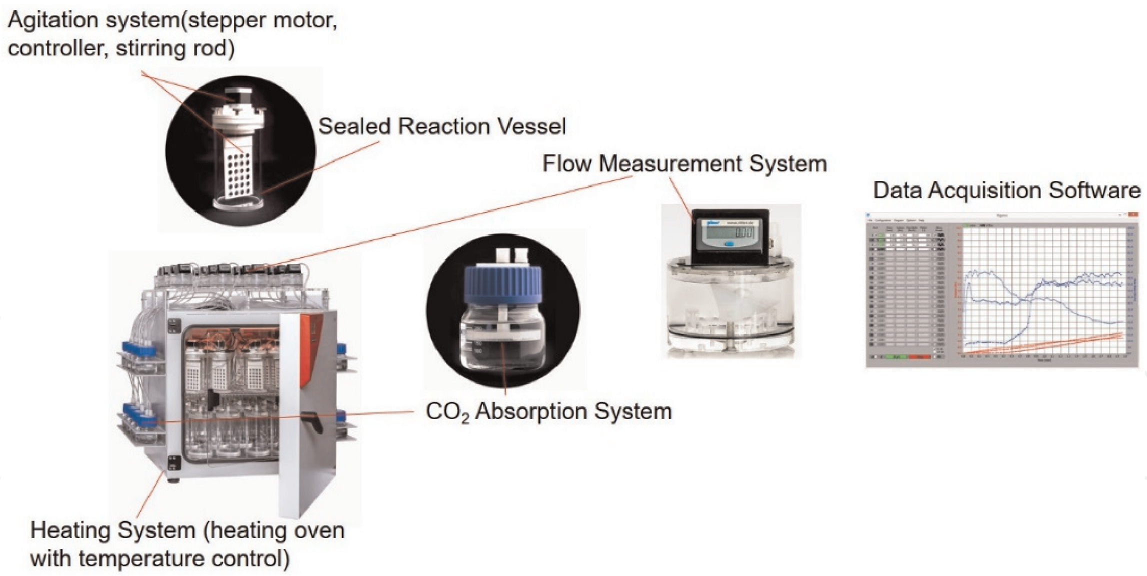

Figure 4.
The biogas batch fermentation system by Ritter [49].

The agitation in the case of the AMPTS is accomplished with an overhead stirrer with a special airtight cap that allows for the stirring of the mixture with a stirring rod coupled to the actuator. Ritter used an overhead stirrer, but the coupling between the actuator and the stirring rod is accomplished with a magnetic coupling. Ritter utilized a heating oven for the temperature control of the mixture, while in AMPTS II a water bath is used. For the ultralow gas flow measurement (ULGFM), Bioprocess Control uses their patented gas flow cell meter which operates based on the liquid displacement and buoyancy working principles, as well as the Hall effect. Ritter's gas flowmeter is based on the same operating principles but utilizes the tipping bucket effect in combination with a Hall effect sensor. For the normalization of the measurement results, a temperature and a barometric pressure sensor are being used. The user can control the speed and the movement direction of the actuator motors through the software.

The main requirements considered by the design team are that the system can reliably operate for the whole duration of the experiment (more than 30 days), the temperature of the mixture inside the reactor vessel is held constant at a prespecified temperature, it offers an automated and accurate flow measurement method, its components and subsystems are gastight in order for the gas to be able to travel through the system without any leakages, and finally the results are presented to the user via a software UI.

After the listing of the design requirements, the design team proceeds with the generation of alternative concepts. For the facilitation of concept generation, the system could be modeled in various ways, such as the scheme shown in **Figure 5**. In **Table 9**, the information about the mechatronic system is presented in terms of energy, material, and information flows [1].

By studying existing automated BMP systems, the design team attempted to model the basic functions of any automated BMP measuring system as a flowchart. This flowchart representation of the system functions is meant to be representative of any automated BMP measurement system and help the design team with the better understanding of the system to be designed.

In [28], a design tree with the subfunctions of a mechatronic object, more specifically an educational firefighting robot, is presented. A representation of the automated BMP system in a manner similar to that design tree is presented in **Figure 5**.

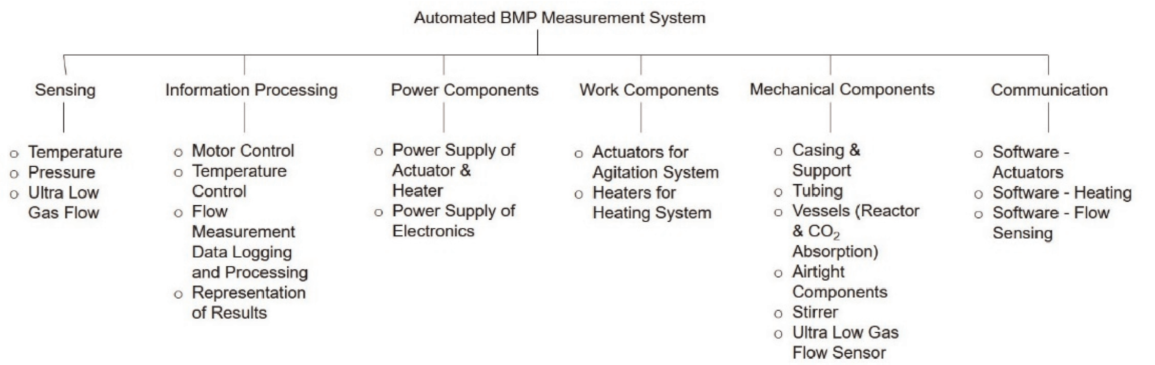

Figure 5.
Design tree for automated BMP measurement system.

Energy flow	Material flow	Information flow
Transformation of electrical power to kinetic energy (agitation)	Flow of gas mixtures through the system	Temperature, pressure, and flow sensing
Transformation of electrical power to thermal energy	Agitation of mixture in the reactor vessels	Control of actuators
		Control of heating element
		Flow sensor data processing and result representation

Table 9.
Energy, material, and information flow representation of the automated BMP system.

The component and component categories that are considered in the design tree in **Figure 5** are the following:

- Sensing: For temperature control inside the reactor vessel, pressure recording and gas measurement.

- Information processing: Software that is responsible for the actuator and temperature control, the data logging and processing of flow measurement values, and the calculation and representation of the experimental results.

- Power components: The power supply of the actuators, the heating elements, and the control and software electronics.

- Work components: The components that produce some kind of work. Mechanical work by the agitation actuators and thermal work by the heating elements.

- Mechanical components: For the casing and structural support of the system, the tubing connections, the vessels (reactor vessel, absorption unit), the stirrer, the airtight components, and the mechanical parts contained within the flow measurement sensor.

- Ultralow gas flow measurement: Working principles incorporated within the gas flow measurement system. In reality, the design of an ultralow gas flow measurement system could be considered by itself as a distinct mechatronic design problem.

- Communication: For the inter process communications between the software and the rest subsystems (actuators, heater, sensors).

Based on the classification of components considered in the design tree of the system (**Figure 5**) and the subsystems considered in the flowchart representation of the system (**Figure 2**), the design team came up with a first set of alternative concepts for the automated BMP system. The alternative components considered are presented in **Table 10**.

As it can be seen in **Table 10**, not all subsystems and components were taken into account in the generation of possible solutions, but this does not mean that the basic requirements of the system are not met by the alternatives that have been chosen. As mentioned in previous sections, the quality and completeness of the solutions depend to a large extent on the available information and knowledge about the design object and the design team experience. It should also be borne in mind that the evaluation of the solutions is an iterative process, the purpose of which is to support the design team in the decision-making processes during the conceptual design phase.

Based on the data of **Table 11**, there are $4 \times 3 \times 2^4 = 192$ possible design solutions. The study of the procedures for reducing the number of solutions lies outside the scope of this chapter and is left for future work. However, some of the factors that may play an important role in rejecting some alternatives without requiring a thorough evaluation process are outlined. The factors are as follows.

- The design team is not familiar with relevant technology [28].
- The assembly/communication between some components is unacceptably complicated or even impossible.
- The cost of some alternatives is too high.
- Some alternatives have already been realized by competitors, and they are not considered innovative enough.
- The alternative does not satisfy the basic system/product requirements.
- The time frame for the design process does not allow for the exhaustive evaluation of the alternatives, and a decision must be made quickly.

Agitation system	Heating system	Temperature sensors	Ultralow gas flow measurement (ULGFM)	Communication
1. Actuator: stepper, DC brushed/brushless, servo 2. Stirrer: overhead coupled stirrer, magnetic stirrer	3. Water bath heater 4. Heating oven 5. Silicon jacket heater	6. Resistance thermometer detector (RTD) 7. Thermocouple	8. Liquid displacement and buoyancy and Hall sensor 9. Liquid displacement and optical sensor	10. Direct, wired between software and subsystems 11. Radio frequency (Wi-Fi) between software and subsystems

Table 10.
Automated BMP measurement system alternatives based on system subfunctions.

Design alternatives	DA_1	DA_2	DA_3
Actuator	DC brushed	DC brushless	Stepper
Stirrer	Overhead with linear coupling	Overhead with linear coupling	Magnetic
Heating	Water bath	Heating oven	Silicon jacket
Temperature sensors	Thermocouple	RTD	RTD
ULGFM	Liquid displacement and optical sensor	Liquid displacement and buoyancy and Hall sensor	Liquid displacement and optical sensor
Communication	Wired connections	Wired connections	Radio frequencies (Wi-Fi)

Table 11.
Three design alternatives selected for evaluation by the design team.

In the same manner, if an alternative presents really low cost and complexity and the design team is very familiar with the relevant technology, it could be chosen for further development along with the alternatives that will be chosen after the evaluation process. The design team came up with the three design alternatives DA_k $(k = 1, 2, 3)$ presented in **Table 11**.

Each design alternative uses a different type of actuator for the stirring of the mixture. In DA_1 and DA_2, a brushed DC motor and a brushless DC motor, respectively, are used. A stepper motor with the additional components for the open-loop control of the system is being utilized in DA_3. As for the other agitation components, DA_1 and DA_2 are using an overhead stirrer which is coupled with the motor with a linear coupling, e.g., helix coupler, while the third alternative makes use of a magnetic coupling between the actuator and the stirrer. The three design alternatives realize the heating of the mixture inside the reaction vessels in three different ways. The two first alternatives, i.e., DA_1 and DA_2, use a water bath and a heating oven, respectively, for the heating of the mixture, while in DA_3 a silicon rubber heater (etch foil heater) is chosen for the heating purposes. Thermocouples (DA_1) and a RTD sensor (DA_2, DA_3) are chosen as alternative solutions for temperature sensing inside the reactor vessel. The two alternatives that the design team came up with for the realization of the ultralow gas flow measurement system are presented in **Figure 6**.

The first alternative for the ULGFMS, presented in **Figure 6a** and used in design alternatives DA_1 and DA_3, utilizes the liquid displacement discipline and with the use of an optical sensor is able to calculate the flow of the produced gas. As gas

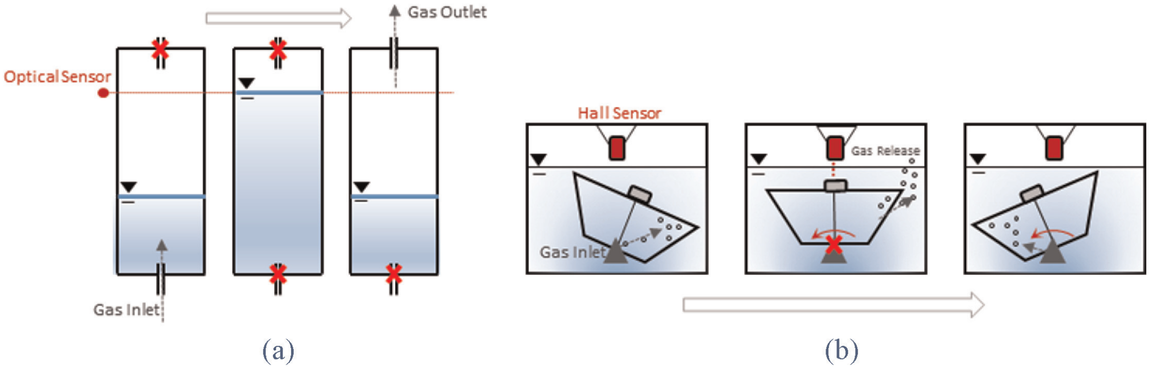

Figure 6.
Ultralow flow measurement alternatives. (a) The liquid displacement discipline. (b) The tipping bucket mechanism.

enters the chamber, pressure arises, and the liquid level inside the chamber rises until it reaches the point where the optical sensor is pointed at. The sensor records the phenomenon, and the gas is then released from the system, the liquid level drops again, and the process repeats itself. By calibrating the system so that we know the exact gas volume needed for the liquid to reach the optical sensor's level and recording the number of times it reaches that level in a given time interval, we can estimate the gas flow. The second alternative presented in **Figure 6b** and utilized in design alternative DA_2 makes use of a tipping bucket mechanism. A bucket-like chamber is placed inside a container packed with a liquid. Gas bubbles enter the bucket, and when enough of them have gathered, the bucket tips because of the buoyancy. During the tipping motion, a Hall sensor records the phenomenon, and the gas is released. As we can see, the second alternative is very similar to the first one. Finally, for the first two alternatives DA_1 and DA_2, the communication between its subsystems will all be achieved via physical (wired) communication protocols and hardware components, while the third DA_3 alternative is using radio frequencies, namely, Wi-Fi communication between its subsystems.

The next step of the conceptual design phase involves the selection of the appropriate criteria for the evaluation of the design alternatives, the determination of their weights, and the interactions between them. In the example of the automated BMP system, five criteria from the total of seven presented in the previous section are considered for the evaluation, along with the cost and complexity criteria. For the cost criterion, the material resources and man-hours required for the development of the system are estimated. Complexity mainly describes the familiarity of the design team with specific technologies, and complex design process will be based on that fact. It should be noted that higher scores on cost and complexity criteria translate to fewer resources needed for the development of the product and also to less complex designs. The score of each alternative with respect to each criterion is shown in **Table 12**.

The fuzzy measures that represent the weight of each criterion are presented in **Table 13**. Three values were chosen to specify the importance of each criterion $(0.05, 0.105, 0.160)$, with each one corresponding to low, medium, and high importance, respectively. As it is stated in [28], a choice of very low and/or very high values limits the ability to define the correlations between criteria. For example, assuming a low importance equal to $\mu(x_1) = 0.01$ and a high importance equal to $\mu(x_2) = 0.20$, then the positive correlation among them is impossible to be defined since the following constraints must be true: $\mu(x_1) + \mu(x_2) > \mu(x_1, x_2)$ and $\mu(x_1, x_2) > \mu(x_2)$.

The design team wanted to reward systems that display low cost and complexity, and so the two criteria are negatively correlated. The same thinking applies to

Criteria (x_i)	DA_1	DA_2	DA_3
1. Configurability	0.01	0.05	0.3
2. Dependability	0.17	0.17	0.17
3. Interaction ability	0.2	0.2	0.3
4. Motion ability	0.25	0.3	0.17
5. Perception	0.14	0.14	0.14
6. Cost	0.5	0.2	0.4
7. Complexity	0.4	0.3	0.3

Table 12.
Evaluation scores.

Criteria (x_i)	Weight ($\mu(x_i)$)
1. Configurability	$\mu(x_1) = 0.16$
2. Dependability	$\mu(x_2) = 0.05$
3. Interaction ability	$\mu(x_3) = 0.105$
4. Motion ability	$\mu(x_4) = 0.05$
5. Perception	$\mu(x_5) = 0.05$
6. Cost	$\mu(x_6) = 0.16$
7. Complexity	$\mu(x_7) = 0.16$

Table 13.
Criteria weights.

Criteria (x_i, x_j)	Interaction	Set weight $(\mu(x_i, x_j))$
Cost/complexity	Negative	$\mu(x_6, x_7) = 0.45$
Complexity/configurability	Negative	$\mu(x_1, x_7) = 0.40$
Interaction ability/configurability	Positive	$\mu(x_1, x_3) = 0.20$
Cost/configurability	Negative	$\mu(x_1, x_6) = 0.35$

Table 14.
Criteria correlations and set weights.

Design alternatives	DA_1	DA_2	DA_3
Evaluation scores	0.2995	0.1960	0.3205

Table 15.
Choquet values of the alternative scores.

two other negative correlations between complexity/configurability and cost/configurability. A system with great configurability allows for the user to customize the BMP system easier and faster, which translates to higher interaction ability levels, and thus, the two criteria are positively correlated. All interactions and the corresponding weights are presented in **Table 14**.

The final evaluation scores of each alternative are presented in **Table 15**. The evaluation scores are the Choquet integral values that were calculated based on Eq. (3). Alternative DA_3 scored the highest score, while DA_1 and DA_2 came up second and third, respectively, as it is shown below. DA_1 and DA_3 present similar performance characteristics, with DA_1 having a marginal lead in cost and complexity performance but falls short on configurability performance.

5. Conclusions

In this chapter, some well-known methods for the conceptual analysis and evaluation during the mechatronic design process are discussed, and a method for the evaluation of generated design alternatives is proposed. The proposed design criteria, which were derived from the multi annual roadmap in robotics in Europe, were presented in [28]. Four interactions between criteria are presented and the Choquet integral along with the two additive fuzzy measures used for dealing with the aggregation of the evaluation scores.

The most useful outcomes of this chapter are as follows. (i) The modeling of the system can lead to a better understanding of the problem and make the evaluation process easier and more accurate. (ii) The proposed mechatronic abilities can be utilized in a number of different situations. However, the score scaling of the criteria needs to be further investigated. (iii) The proposed method is there to support the design team on the selection of the most suitable design alternative. The evaluation process and the results obtained from it are dependent on the experience of the design team, the number of people participating in the evaluation, and the available knowledge at the time the decision is made.

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