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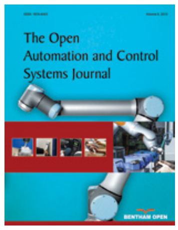

RESEARCH ARTICLE

An Optimization-Based Embodiment Design Approach for Mechatronic Product Development

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Abstract:

Objective:

This paper deals with the design and the optimization of mechatronic devices.

Introduction:

Comparing with existing works, the design approach presented in this paper aims to integrate optimization in the design phase of complex mechatronic systems in order to increase the efficiency of this method.

Methods:

To solve this problem, a novel mechatronic system design approach has been developed in order to take the multidisciplinary aspect and to consider optimization as a tool that can be used within the embodiment design process to build mechatronic solutions from a set of solution concepts designed with innovative or routine design methods.

Conclusions:

This approach has then been applied to the design and optimization of a wind turbine system that can be implemented to autonomously supply a mountain cottage.

Keywords: Mechatronics, Embodiment design, Multidisciplinary design optimization, Combinatorial optimization.

1. INTRODUCTION

Designing a product aims to translate a certain amount of information expressed as a need to a technical description of a concrete solution that meets that need. In a very competitive economic context, companies should provide innovative and efficient products while remaining competitive. To perform this, they should frequently renew their product line and deal with even more constraints and more stringent standards, related to environment for example. However, the design products are always more complex and have increasingly more functionalities that imply an increasing level of invention [1] and integration of technologies from several fields. The evolution of devices like aircrafts, smartphones and home automation devices exemplifies this statement.

It is within this context that mechatronic systems [2] appeared forty-five years ago. These systems are defined by AFNOR [3] as an "approach aiming at the synergistic integration of mechanics, electronics, control theory, and

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computer science within product design and manufacturing, in order to improve and/or optimize its functionality". A mechatronic system must then be able to perceive its environment, process the information, communicate and act on its environment and should have a high level of integration in both the functional and physical viewpoints. Actors with different and complementary skills should therefore collaborate in an efficient way to better satisfy the needs expressed by the customer.

Based on [4, 5], a mechatronic system therefore involves at least four different modules (Fig. **1**):

- A "base structure", which often consist of a mechanical structure or a material,
- One or more actuators that can act a machine or a process to change its behavior or states,
- One or more sensors to provide information on the current state of the machine that can be analyzed and processed by an information processing device,
- One or more information processing device, often a computer or an embedded system, analyze and process the information given by the sensors and control the actuator to obtain the desired behavior. The control law synthesis consists of the main part of these processing devices.

In the classical design process [6], tools such as TRIZ [1, 7, 8] are used to define solution concepts that are more or less abstracted representations of the system. These concepts should then be concretized as technical solutions and then as mechatronic devices. This translation is one of the more delicate stages of the design process as it relies on the creativity of the designers and their capabilities to implement concepts into feasible solutions and to integrate them into the final mechatronic product. This activity dealing with the embodiment design of mechatronic devices is the heart of the work presented in this paper.

The embodiment design activity is confronted with a certain amount of conceptual, methodological and technical barriers, mainly due to the lack of a viewpoint shared by all stakeholders [9] involved in the design or, later, the evaluation of the solution. Then, the expressed needs associated with actual standards and laws often lead to the onset of conflicting goals that can be difficult to solve for the designers.

Multidisciplinary designers can also lead to other difficulties related to the communication between them. Thus, special attention should be given to the influence of the choices and the designers' skills on the resulting solution, which often leads to a non-optimized solution regarding its performances, its functionalities and its level of integration. The abstraction level of the solution during this stage indeed implies that these solutions are expressed in an imprecise and incomplete manner. But, the first decisions made the earliest in the development process have the strongest effect on the efficiency of the final solution and may impact more than 70% of the global product life cycle cost [10 - 12].

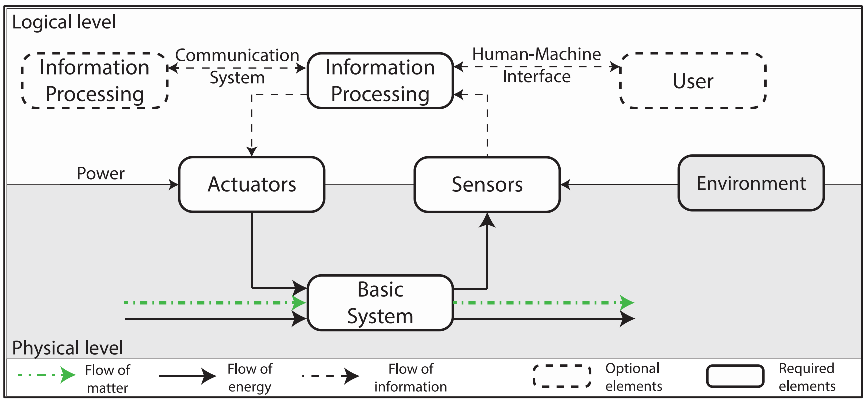

Fig. (1). General structure of mechatronic systems [4].

The contribution presented in this paper deals with the use of optimization tools to build, using a semiautomatic approach, mechatronic devices in order to systematize the choice of the best solutions for the desired performances while reducing the influence choices and skills of the designers on these results. However, optimization is usually placed too late in the design process and is limited to identification for optimal parameters in the detailed design. But, placing one or more optimization phases during the phase of architectural development would increase the influence of the optimization process because the decisions taken earlier in the process are those most impact on the performance and cost of the life cycle of the product. Similarly, the use of optimization methods for influencing both the architecture and the parameters of the system should also increase this impact.

This paper is structured in four parts. In the first part, a literature review is presented to identify the problems implied by the integration of optimization in the embodiment design stage of mechatronic systems. Then, in the second part, the contribution regarding the development of an approach to optimize and design mechatronic systems is then detailed. The third part explains how the approach can be applied to an example case study. And finally, in the fifth part, the contribution is summarized and possible improvements and outlook are exposed.

2. LITERATURE REVIEW

This section presents a literature review of past contributions in the fields of the embodiment design, the design optimization and finally the use of optimization as an embodiment design approach to improve the architecture and the parameters of complex mechatronic or multidisciplinary devices.

2.1. Design Models

In 1977, two German professors, G. Pahl and W. Beitz [6] modeled the process used to design new products. This representation has four steps:

- The definition phase,
- The conceptual phase which aims to propose abstract or technical concepts that may solve the requirements,
- The embodiment step which should offer technological solutions to implement the proposed concepts,
- The detailed design phase, which should help preparing (detailed drawings, manufacturing steps…) the manufacturing phase of the product or its prototype, before placing it on the market.

On a sequential engineering process, tasks begin only if the previous one is already completed. For reasons of cost and design time, this approach, after the sequential engineering was gradually abandoned in favor of concurrent engineering (Fig. **2**), where the several steps are done in parallel [13 - 15].

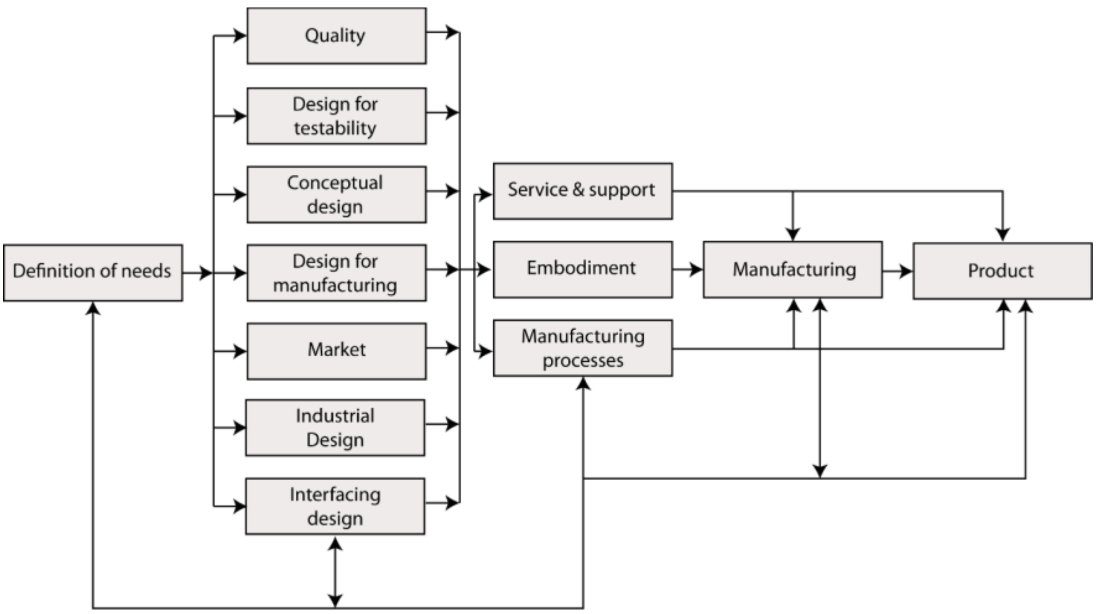

Fig. (2). Flow chart diagram of the concurrent engineering process [14].

With simultaneous engineering, tasks overlap; resulting in a gain of time can be devoted to other activities of the design process and product development [16]. This vision of the engineering process, originally developed during World War II [17], is still valid. In this section, we use the term “concurrent engineering” to refer to issues related to competitive factors, concerns and constraints derived from downstream business process design and development [18]. One of the definitions of concurrent engineering, which stresses the importance of downstream activities in the process of design and development [19] “Concurrent or simultaneous engineering is the study of factors associated with the life cycle of the product during the design phase. These factors include product functionality, manufacture, assembly, testing, maintenance, reliability [20], dismantling [21], safety [22].” This description is supplemented by other authors stressing the parallelization of activities within the design and development processes [23] and interaction of business actors [24]. The challenge of integrating all business and constraints life cycle of a product in its development phase, is still relevant. In 2004, the Society of German Engineers (Verein Deutsche Ingenieure) has published a practical guide [4] advocating the use of the V-cycle presented in (Fig. **3**) for the systematic development of mechatronic systems. This approach has been adopted by the mechatronic community and is one of the concurrent engineering approaches.

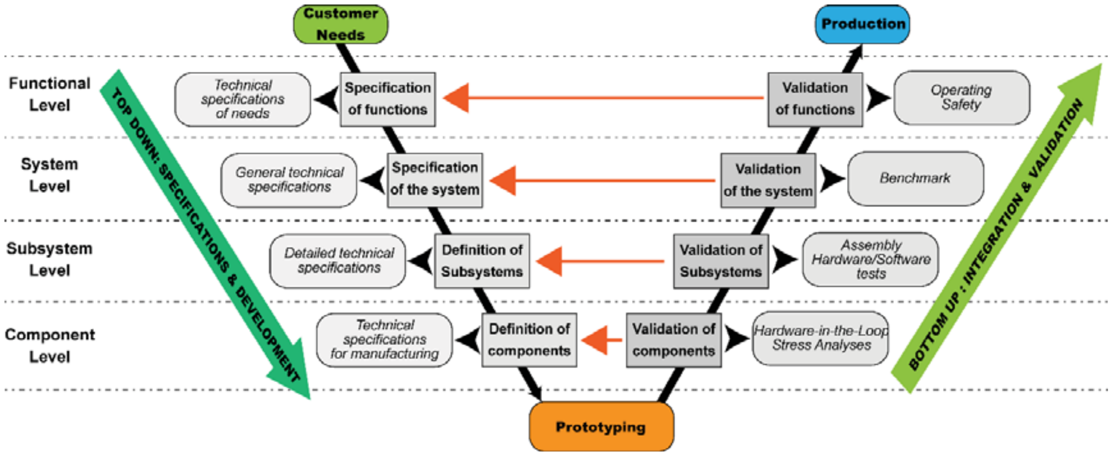

Fig. (3). V-cycle for the design of mechatronic systems [4].

This process has two successive phases [4, 25]:

- The specification and design phase (“top-down”)
- The integration and validation phase (“bottom-up”)

As part of our research works [26 - 28], we placed them in the context of concurrent engineering, especially around the design cycle V, which has the advantage of being a recognized model by the mechatronic community.

2.2. Embodiment Design

This paragraph focuses on the embodiment design process defined by Pahl and Beitz [6] as the part in which the design solution is developed starting from the principle solution or concept of the technical product. This step is considered as particularly complex because many actions must be performed simultaneously; several steps should be repeated at a higher level of information and additions or alterations in one area may have repercussions on the design in other areas.

The classical embodiment approach, presented in [6], can be separated in three main steps:

- The first step starts from the design concept and aims to develop preliminary solutions that meet the customer requirements;
- The second step to develop detailed solutions from the preliminary solutions designed in the first step.
- After the preliminary solution is designed, evaluation and verification phases are performed to check the solution regarding technical and economic criteria.

In this approach, the optimization is performed in the third step to eliminate the weaknesses of the solution designed in the two previous steps. This means that the optimization is considered as a tool to improve and correct a solution, not as a manner to computerize the design process of a system. This design process remains a manual process the designer should perform.

However, the design process of mechatronic is particularly complex and several research works have been performed to develop design support tools to make the designer’s task easier.

2.3. Mechatronic Design Support

2.3.1. Guideline for Mechatronic System Design (VDI 2206)

In 2004, the German Society of Engineers issues the VDI 2206 [4] guideline that is a functional modeling methodology based on the V-model. The functional modeling methodology means that different methods are used to define a model of any system by capturing and processing the information about its purpose and the functions of its components to fulfill the purpose [29]. This VDI guideline represents a practice-oriented guideline for the systematic development of mechatronic systems and consists of three elements [4] the V-model on the macro level, a general problem-solving cycle on the micro level, and predefined process modules for handling recurrent working steps in the development of mechatronic systems.

As presented in (Fig. **4**), it also divides the mechatronic design process in four stages: the system design, the domain-specific design, the system integration and the assurance of properties [29]. During the system design phase, a cross-discipline solution concept is defined for the system. During the domain-specific design, several parallel smaller design tasks are performed. The results regarding these tasks are integrated to the overall mechatronic system during the system integration phase. Finally, the assurance of properties aims to ensure that the results of the system fulfill the solution concept defined during the system design phase. If the system needs improvements, the design process is repeated until the assurance of properties succeeds.

This VDI2206 provides a practice-oriented guideline for mechatronic system design which unifies the domain-specific design more systematically [29] but it suffers from several drawbacks:

- The interfaces among the subsystems of different design domains do not arouse enough attention in this organizational method [29].
- An explicit link between the different engineers does not exist.
- The mechatronic system design process based on this guideline may involve an important number of iterations to fit the requirements according to the assurance of properties step.
- The mechatronic system is not explicitly optimized during the process.

To reduce the number of unnecessary iteration loops during the design process of complex mechatronic systems, one another design method; the hierarchical design method is presented in the follow paragraph.

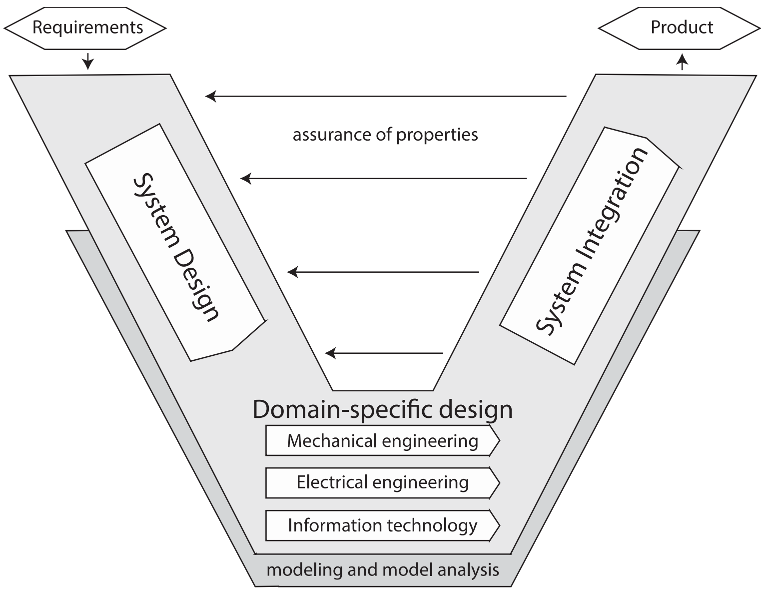

Fig. (4). VDI2206 guideline for mechatronic design [4].

2.3.2. Hierarchical Design Method

The hierarchical design method considers the integration problem of the different technologies of a mechatronic device from the early design stages [30]. Mechatronic systems can be separated into domain-specific subsystems characterized by a "model pillar" and only the first and highest level has an interface with the other pillars, the other subsystems *via* the mechatronic coupling level (Fig. **5**).

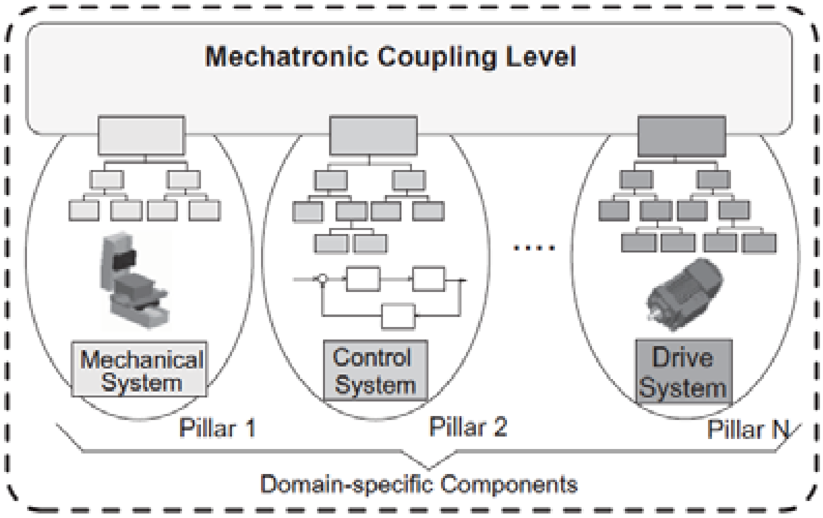

Fig. (5). Mechatronic system and model pillars [30].

Based on the four design domains [31] and the axiomatic design principles, the functional requirements of a given model pillar is defined using several design parameters. In the hierarchical design model, one functional requirement at level i can affect several functional requirements at level i+1 based on the design parameters. These design parameters are classified in two categories: the internal parameters that are exclusively used at a local stage and the external parameters that are shared between the different design levels (Fig. **6**).

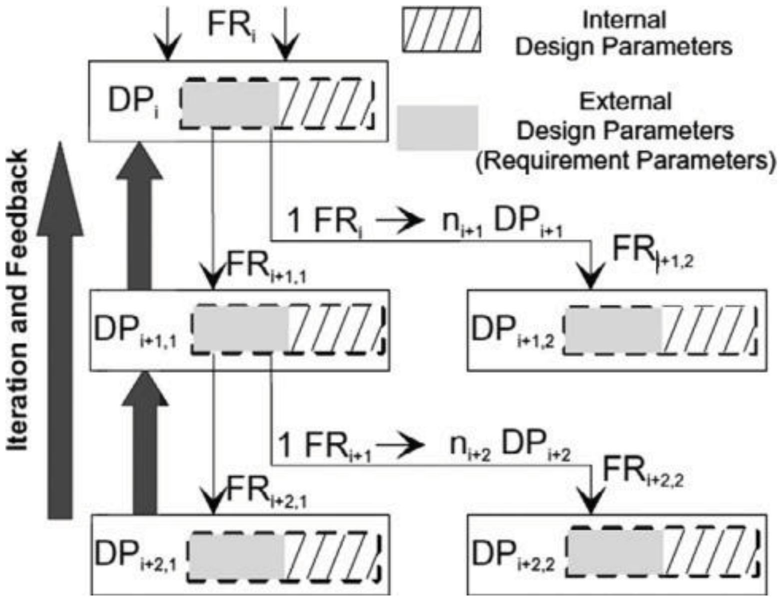

Fig. (6). Hierarchy of parameters [30].

The hierarchical design model has been proposed to address complex design tasks during the mechatronic development phase. In these tasks, the discipline-specific design does not need to be fully integrated on the mechatronic design level. By analyzing the interactions between the design parameters and the functional requirements, it enables an easy qualification on how a product should be designed to reduce unnecessary iteration loops [29]. Different modeling levels have therefore been proposed to reduce iteration loops [30] models based on characteristic diagrams and table data, simple analytical model, finite-element model including nonlinear effects. These levels help reducing the number of tasks the designer should perform and reducing the number of design parameters.

In [30], Hehenberger considers the optimization from the second level (simple analytical model) but it is reduced to a search for optimal parameters of a parametric model which is not affected during the process, which classifies the use of optimization as a tool to improve an already-designed system within the re-design phase which, as introduced in [10], only has a limited effect on the results because it is constrained by the choices made during the development phase. In the next subsection, the contributions regarding the use of optimization in design engineering are presented.

2.4. Optimization in Mechatronic Design

This subsection presents an overview of uses of optimization in mechatronic design engineering.

2.4.1. Multidisciplinary Design Optimization (MDO)

Most the research works in mechatronic design optimization are focused on the research for multidisciplinary design optimization methods. These methods [32 - 35] such as Multi Discipline Feasible, All-in-once or Collaborative Optimization help the designer to consider the interaction between the different disciplines of a mechatronic device. The different methods differs from the manner how these interactions are included during the optimization process or the number of optimizers required during the process. For example, Multi Discipline Feasible and All-in-once methods are considered as single level MDO approaches as it requires only one optimizer and they use subsystem evaluators or analyzers to identify the behavior of the subsystems. The collaborative optimization exemplifies the multilevel methods where subsystems are optimized once (local optimization) and then results of all the monodisciplinary subsystems are integrated in the overall mechatronic system and a final optimization process is performed to integrate the interactions.

2.4.2. Uncertain MDO

As introduced in subsection I.2, the embodiment design phase aims to develop solution layouts starting from a set of concepts. The resulting solution should then be represented as an imprecise and an incomplete manner. To ensure the results of the final solution, at the end of the design process, will not be too different from the results obtained for the solution layout, some tools and methods were developed to integrate uncertainties [36] in the design process. (Fig. **7**) presents two categories of uncertainty-based application: robustness based on six-sigma analysis methods and reliability.

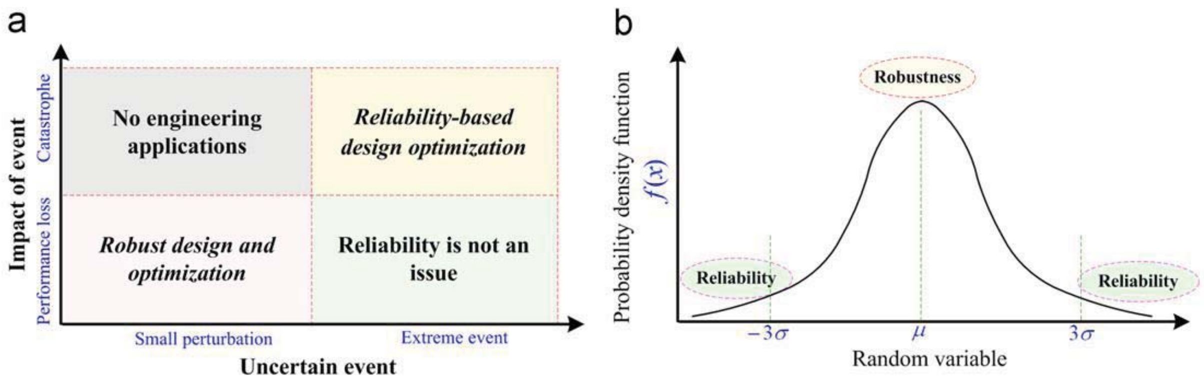

Fig. (7). Two categories of uncertainty-based design [36]: (a) uncertainty-based design domains and (b) robustness and reliability in terms of probability density function.

These methods use stochastic probability laws and properties or Monte Carlo simulation methods to evaluate the robustness or the reliability of the system. These methods are integrated in the classical MDO methods or in the optimization problem (by defining robustness criteria for example).

2.5. Need of a Design Support Tool for Mechatronic Embodiment Design

In the previous paragraphs, MDO and uncertain MDO were introduced. These methods are used to take the interaction between the different fields and subsystems during the optimization process. However these methods should be classified as parametric optimization approaches that can only be used as a parameter identification tool for sizing problem solving. This statement classifies MDO as a redesign process or as a tool used in detailed design phases to improve the performances and the efficiency of an already-designed system.

To better improve the efficiency of the optimization process, an extension of MDO should be done so it may also act on the structure or the architecture of the solution. In the problem considered in this paper, the optimization should also be intended to the optimal design of mechatronic systems during the architectural development (embodiment).

3. CONTRIBUTION: THE NOVEL OPTIMIZATION INTEGRATED-DESIGN APPROACH

To improve the optimization so that it can be used as a design tools that can be integrated in a design support methodology to improve the efficiency of mechatronic systems. In this section, the design approach that is the heart of the contribution presented in this paper is developed. To solve the different problems presented in the previous sections, a novel design approach to integrate optimization in the embodiment design process of mechatronic systems has been developed.

Fig. **8** presents the global optimization integrated-design approach based on the VDI 2206 guideline. It contains four main phases:

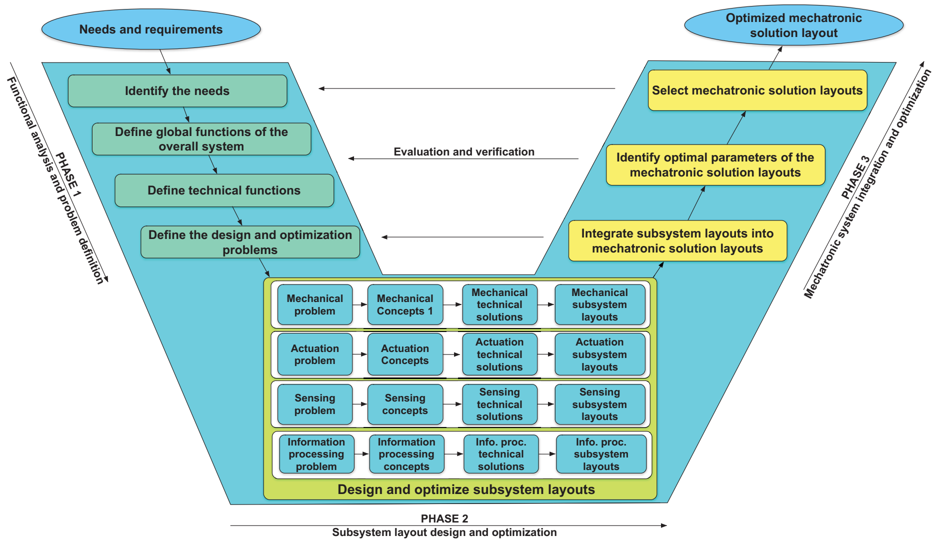

Fig. (8). Optimization-integrated approach for embodiment mechatronic design.

- In the first phase (“top-down”), the needs, the global and technical functions as well as the design and optimization problems are identified and defined.
- In the second phase aims to design and optimize subsystem layouts for each monodisciplinary component or module from the overall mechatronic system.
- In the third phase (“bottom-up”), the modules (designed during the second phase) are integrated into mechatronic solution layouts. These solutions are then sized (parametric optimization) and best layouts are selected and evaluated to ensure the results of the layout fit the expected requirements.

These phases are detailed in the following subsections.

3.1. Phase 1: Functional Analysis and Problem Definition

This phase aims to define the input data and functions that will be used during the design process. During this phase, four actions are performed:

- First the needs are identified;
- Then global functions (service or constraint functions) are defined for the overall system;
- Then these functions are decomposed into several technical functions;
- Finally, the design and optimization problems are determined.

These actions are detailed afterwards.

3.1.1. Step 1.1: Identify the Needs

The first step aims to identify the needs and the requirements that correspond to the objectives of the design process. To perform these identifications, APTE[1] method [37] or SysML[2] [38] requirements diagram may be used. When using APTE method, it leads to the definition of the bull chart to identify:

- To whom is the product useful?
- On who/what does the product have an effect?
- For what purpose is the product prepared?

A stability study may be performed to identify why does the need exist and what may alter or suppress the need.

3.1.2. Step 1.2: Define Global Functions of the Overall System

Based on the identification of needs, a functional analysis is realized to define the global functions of the overall system.

This analysis should define three different types of functions:

- The main functions (service functions) that correspond to the functions those satisfy the expressed needs and are the reasons why the product should be developed. For example, for a mobile phone, the main function will be "phone from everywhere".
- The constraint functions that will principally have force the system characteristics and define conditions the product must always verify. These functions will for example consist of constraints imposed by current environmental and technical standards or laws, regarding the safety, the reliability or by the customer.
- The complementary functions, that facilitate, improve or supplement the provided service but do not result in an expressed demand by the customer. For the mobile phone, these functions correspond to the auxiliary functions such as messaging services, music listening, …

The final solution will strongly depend on this analysis: most of the differences between two products having the same main functions result from the constraint and complementary functions.

3.1.3. Step 1.3: Define Technical Functions

Once the global functions have been identified, these functions should be successively decomposed in a set of technical functions and, finally elementary (monodisciplinary) functions using FAST [39 - 41] (Function Analysis System Technique) method.

3.1.4. Step 1.4: Define the Design Specifications

Based on the global functions, the design specifications and the optimization problems may be defined by identifying, for each function:

- Criteria that can be used to evaluate the global function,
- For each criterion, an expected quantitative or qualitative level is defined. This level represents the expected target of the design process.
- A tolerance level is also integrated to define the limits of acceptation of a solution. This tolerance level may be used to identify which criteria (for example those related to safety) are more critical than the others.

In the first phase, the input data of the subsystem layout design and optimization phase have been defined and identified. In the next subsection, the second phase related to the design of the modules and subsystems of the overall mechatronic system is detailed.

3.2. Phase 2: Subsystem Layout Design and Optimization

Based on the global problem and the functional decomposition, monodisciplinary subproblems can be elaborated.

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[1] http://www.methode-apte.com

[2] http://www.sysml.org

These subproblems can be related to the mechanical structure, the actuation, the sensing or the information processing subsystem design. They also define the goals for the layout design process for each design subproblem. (Fig. **9**) presents the principle of the second phase from the optimization-integrated design approach for mechatronic systems development. This phase involves four actions that will be detailed in the following paragraphs:

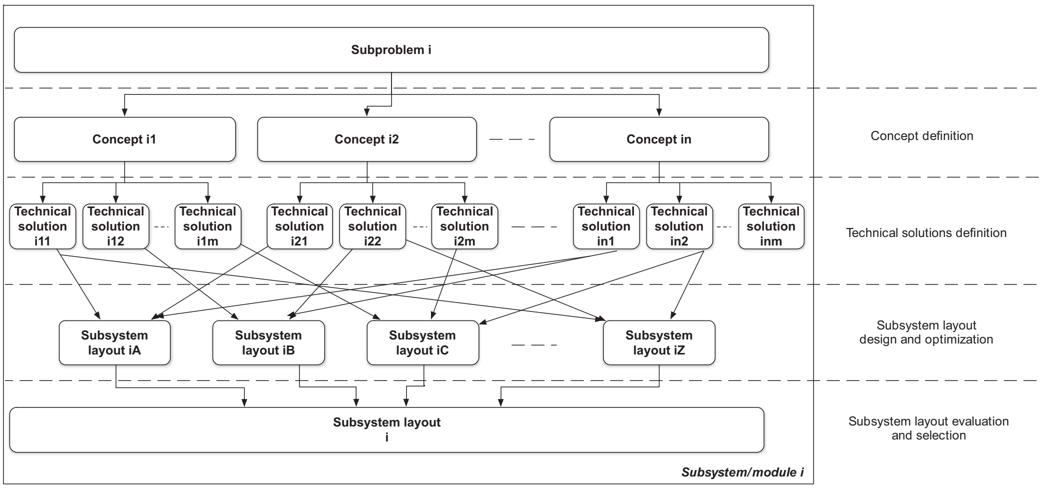

Fig. (9). Subsystem layout design and optimization principle.

- Following the subproblem definition, concepts that can be used to solve the problem are elaborated and designed using either inventive or routine design methods.
- These concepts should then be concretized. Using solution databases, technical solutions that realize defined concepts are built. Case-Based Reasoning approaches may be considered to perform this action.
- The technical solutions are then integrated into candidate subsystem layouts using combinatorial optimization approaches. If the subproblem has more than one objective, the optimization process leads to a multiple number of candidate layouts.
- One or a few subsystems are selected using multicriteria analysis or decision-making approaches to remove worst and outlier subsystem layouts.

3.2.1. Step 2.1: Concept Definition

In this step, the concepts or principles of solution should be defined. To do this, the designer has mainly two options:

- The first option reuses and adapts existing concepts. In order to determine these concepts, we can search these concepts using FAST or, in the case the concepts does not sufficiently fit the specifications, case-based reasoning can be used to define these concepts [42] by adding an adapting step, so as to modify and combine concepts from a solution base to obtain a better concept.
- The second option relies on the development of new concepts in the conceptual design phase, using inventive design techniques, like the Theory for Inventive Problem Solving (TRIZ) [1].

In most cases, to reduce system design costs, reusing existing concepts (first option), rather than creating a new concept (second option) is preferred. A contradiction is for example characterized by the fact that the improvement of technical parameter degrades another technical parameter. From these contradictions, one of the options presented above is used to define a set of operating principles that solve these contradictions. All of these operating principles constitute the solution concept. These concepts include the ability to characterize the functionality of the system whose structure must be designed to achieve these solution concepts.

3.2.2. Step 2.2: Definition of Technical Solutions

Once the concepts that solve the design problem are built, either by defining new concepts or reusing and adapting existing concepts, the properly known design phase can be performed to build technical solutions for each function. These solutions will subsequently form a subsystem of the overall mechatronic solution. To achieve this step, the case-based reasoning approach is used to build technical solutions that realize the defined concept by reusing existing solutions from a solution base. If required these solutions can be adapted to better fit the specifications or the design goals. These solutions are presented using the morphological matrix, as shown in (Table **1**), which synthetizes the technical solution (TS) design process for each technical function or concept.

Table 1. Example of morphological matrix.

	1	2	3	4	5	…	m
Function 1	TS_{11}	TS_{12}	TS_{13}	TS_{14}			
Function 2	TS_{21}	TS_{22}					
…							
Function n	TS_{n1}	TS_{n2}	TS_{n3}	TS_{n4}	TS_{n5}	…	TS_{nm}

3.2.3. Step 2.3: Optimization and Design of Subsystem Layouts

Following the design of technical solutions for the different functions and concepts, these solutions must then be integrated in candidate homogeneous subsystems layout. To do this, the eventual dependencies and incompatibilities between the solutions must be identified. This identification process uses the Design Structure Matrix (Table **2**) to easily synthetize these relations. To fill this matrix, the following principle can be used: +1 for dependence relations, 0 for independent solutions and -1 for incompatible solutions.

Table 2. Example of design structure matrix.

	TS11	**TS12**	**…**	**TS14**	**TS21**	**TS22**	**…**	**TSn1**	**TSn2**	**…**	**TSnm**
TS11					+1						-1
TS12											
…											
TS14								+1	+1		
TS21	+1										-1
TS22											
…											
TSn1											
TSn2		-1									
…						-1					
TSn3											

Based on this Design Structure Matrix, combination rules may be defined (Table **3**).

Table 3. Dependency and incompatibility relations (A, B and C represent different technical solutions from the morphological matrix).

Relationship	**Parallel**	**Sequential**	**Conditional**	**Coupled**
Dependency relations	A B A B	A B A B +1	A B C A B +1 +1	A B A +1 B +1
Incompatibility relations	A B A B	A B A B -1	A B C A B -1 -1	A B A -1 B -1

Based on the morphological matrix, if is the number of technical solutions that can be used to realize the function F_j, then the number of possible combination C can be estimated as:

$$C = \prod_{j=1}^{n} m_j \qquad \textbf{(1)}$$

If the number of solutions and/or functions becomes important, all these combination cannot be evaluated in a manual manner and optimization tools should be considered to reduce the subsystem design process. To build the subsystem layouts, stochastic optimization approaches, such as genetic algorithms can be considered to combine the technical solutions and propose optimized subsystem layouts to the designer. Based on the characteristics of the subproblems (number of objectives), more than one solution may be proposed.

3.2.4. Step 2.4: Subsystem Evaluation and Selection

In this step, the solutions are evaluated against technical and economic criteria. Then, decision support approaches, such as Electre, Prométhée [43] can be apply to integrate designer performances in the process and select the best solutions among those designed using the previous combinatorial optimization step.

In this phase, subsystem layouts have been designed and genetic algorithm approaches have been considered to combine technical solutions in order to solve each monodisciplinary sub-problem. These subsystems should now be integrated into the overall mechatronic system. This process is the heart of the third phase detailed in the next subsection.

3.3. Phase 3: Mechatronic System Integration and Optimization

This phase aims to integrate the subsystem layouts, developed during the previous phase, to design candidate solutions for the mechatronic system. This phase considers three steps that are detailed afterwards. The first step is responsible of the integration process and lead to the development of candidate mechatronic solutions. The second step aims to size the obtained mechatronic solution in order to identify optimal parameters of the solutions. The third and final step evaluates and selects the best mechatronic solution regarding technical and economic criteria.

3.3.1. Step 3.1: Integrate Subsystem Layouts Into Mechatronic Solutions

The subsystem layout can be synthetized in the morphological matrix presented in (Table **4**). S_m, S_a, S_s, S_i respectively correspond to the subsystem layouts for the mechanical, actuation, sensing and information processing part.

Table 4. Global morphological matrix for the overall mechatronic system.

	1	2	3	4	5	…	m
Mechanical structure	S_{m1}	S_{m2}	S_{m3}	S_{m4}			
Actuation	S_{a1}	S_{a2}					
Sensing	S_{s1}	S_{s2}	S_{s3}				
Information processing	S_{i1}	S_{i2}	S_{i3}	S_{i4}	S_{i5}	…	S_{im}

Based on the morphological matrix, if is the number of technical solutions that can be used to realize the function F_j, then the number of possible combination C can be estimated as:

As for the subsystem layout design process in phase 2, the Design Structure Matrix is used to identify relationships between the different subsystems and combinatorial optimization approaches are used to combine the subsystems and integrate them in global mechatronic solution layouts.

3.3.2. Step 3.2: Identify Optimal Parameters of the Mechatronic System Layouts

Parametric optimization is performed in parallel for each resulting mechatronic system to identify the optimal parameters. The criteria and constraints from the global optimization problem are used to evaluate the solutions during the optimization process.

3.3.3. Step 3.3: Select Mechatronic Solution Layouts

A final evaluation and selection process is performed upon resulting optimized mechatronic solution layouts. This process should select the best solution regarding global technical and economic criteria defined in the first phase (functional analysis and problem definition). The solution is finally evaluated during the fourth phase to ensure the results of the system fulfill the defined needs and requirements. If the system needs improvements, the design process is repeated until the evaluation process succeeds.

4. CASE STUDY: WIND TURBINE DESIGN

In the previous section, the global optimization-integrated design approach for mechatronic system development and optimization were detailed and presented. In this section, the application of the presented approach to a case study is exposed. This application deals with the development of a medium power wind turbine for autonomously supplying a high mountain cottage closed to the “Petit Mont-Cenis” with electricity. This autonomy implies that the wind turbine should meet the energy needs of the cottage without the need of external sources and without any connection to the electricity grid. (Fig. **10**) summarizes the application of our design approach to the case study. The three different phases are exposed in next subsections.

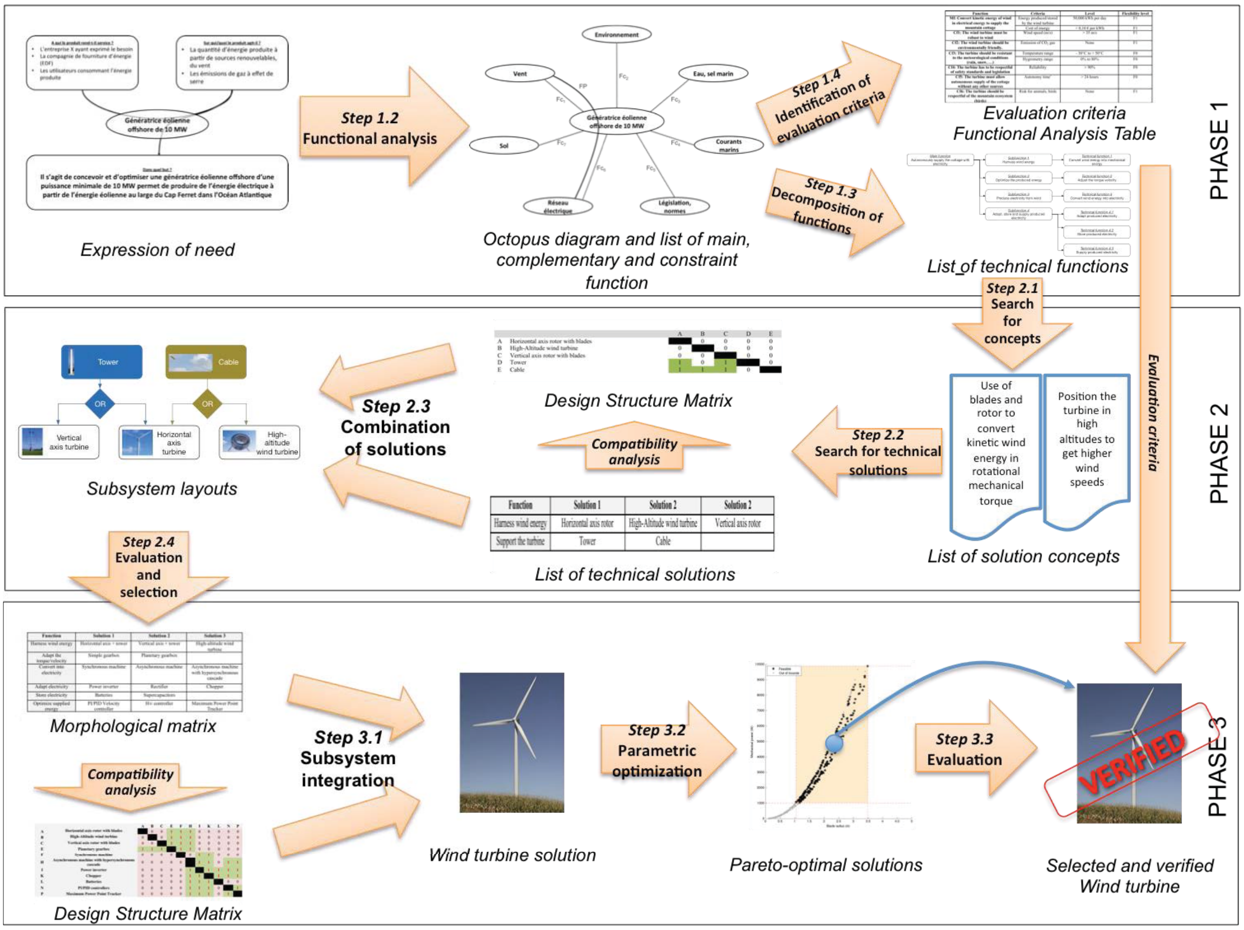

Fig. (10). Application of the proposed approach to the design of a wind turbine.

4.1. Phase 1: Functional Analysis and Problem Definition

Considering the global design process regarding the development of a wind turbine to autonomously supply a mountain cottage with electricity, the first phase has been performed together with the company in charge of the project in order to express the objective, the constraints and the requirements of the design process.

4.1.1. Step 1.1: Identify the Needs

Starting from the need expressed by the client, functional analysis tools were considered to better identify the need using the beast horn diagram. Using this diagram, we identified that the product should be useful for the inhabitant, the host and the guests of the mountain cottage. This product does act on the cottage that is supplied with the produced energy electricity and the electricity produced by converting the wind. The need expressed by customer is to design a wind turbine to autonomously supply a mountain cottage with electricity.

4.1.2. Step 1.2: Define Global Functions of the Overall System

Once this need has been expressed, the external elements were first clarified before identifying the relationships with the environment of the wind turbine. These relationships are then expressed as service and constraints functions that constitute the functional architecture of the wind turbine. Using the octopus diagram, we identified the following global functions of the wind turbine. Based on the need expressed in the previous step, we defined one main function regarding the wind turbine that should “Convert kinetic energy of wind in electrical energy to supply the mountain cottage”. It has been supplemented by several constraint functions expressing for example that the wind turbine must be robust to wind, environmentally friendly, resistant to the meteorological conditions (rain, snow…).

4.1.3. Step 1.3: Define the Technical Functions

In this step, we decomposed the functions expressed in the previous step (step 1.2) to obtain sub-functions, then technical and elementary functions. The main function of the design problem: “Autonomously supply the cottage with electricity” has been developed in order to express sub-functions for the wind turbine (Fig. **11**).

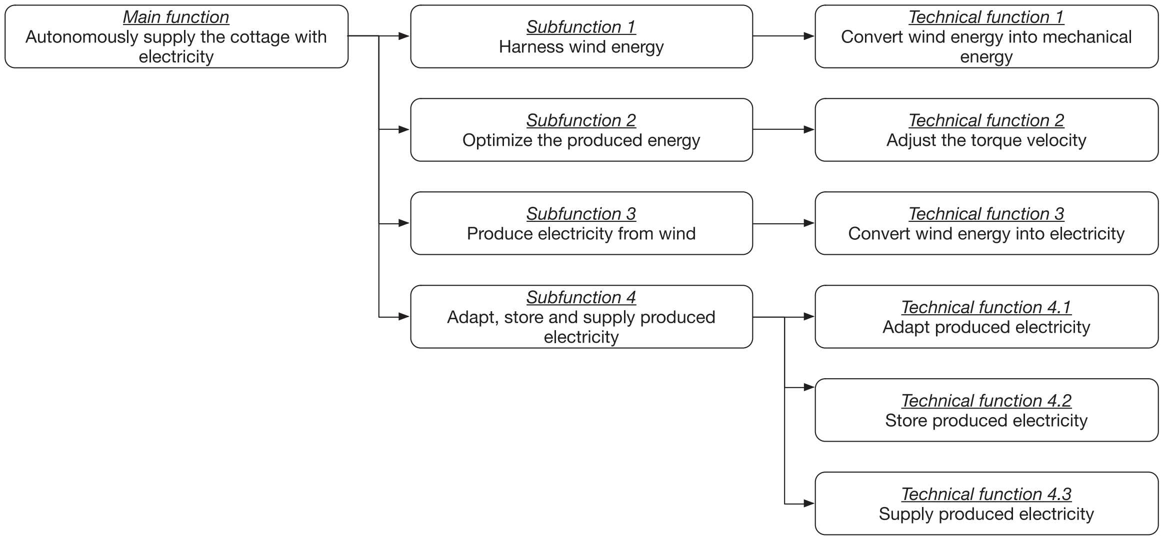

Fig. (11). Functional architecture of the wind turbine.

4.1.4. Step 1.4: Define the Design Specifications

Table **5** presents the evaluation criteria that have been set up along with levels expressing the expected target. These evaluation criteria will be considered in the selection and evaluation process in order to qualify the satisfaction level of one solution compared with the functional architecture defined in this phase. The flexibility levels set for each criterion allows defining if the expressed level can be let unsatisfied and the associated acceptation levels: F0 defines the criterion is not flexible and F3 that it is fully flexible.

Table 5. Expression of evaluation criteria and levels for the wind turbine.

Function	Criteria	Level	Flexibility level
Mf: Convert kinetic energy of wind in electrical energy to supply the mountain cottage	Energy produced/stored by the wind turbine	50,000 kWh per day	F1
	Cost of energy	< 0,10 € per kWh	F1
Cf1: The wind turbine must be robust to wind	Wind speed (m/s)	> 35 m/s	F1
Cf2: The wind turbine should be environmentally friendly.	Emission of CO_2 gas	None	F1
Cf3: The turbine should be resistant to the meteorological conditions (rain, snow…)	Temperature range	- 30°C to + 50°C	F0
	Hygrometry range	0% to 80%	F0
Cf4: The turbine has to be respectful of safety standards and legislation	Reliability	> 90%	F0
Cf5: The turbine must allow autonomous supply of the cottage without any other sources	Autonomy time[3]	> 24 hours	F0
Cf6: The turbine should be respectful of the mountain ecosystem (birds)	Risk for animals, birds	None	F1

4.2. Phase 2: Subsystem Layout Design and Optimization

During the first phase, the functional architecture of the wind turbine has been defined. The second phase aims designing technical solutions. These technical solutions will then be integrated into subsystems using combinatorial optimization tools. The obtained subsystems will later be integrated into the mechatronic system (phase 3). In this phase, we focused on the concretization of the problem regarding the conversion of wind energy into mechanical torque (function "Harness wind energy"). The process is similar for the five other functions.

4.2.1. Step 2.1: Concept Definition

However inventive concepts might be designed to solve the design problem or some of the subsystems using tools such as TRIZ, we decided to consider reusing existing solution concepts as the concept design is not considered in this paper. This concept search process allows us to define the concepts for the different technical functions presented in (Table **6**). For the function "Harness wind energy", we expressed three solution concepts:

Table 6. Expression of technical solutions for the wind energy conversion subsystem.

Solution concept	Technical Solution 1	Technical Solution 2
Use of blades and rotor to convert kinetic wind energy in rotational mechanical torque	Horizontal axis rotor	Vertical axis rotor
Maintain the turbine in high altitudes	Tower	Inflatable structure filled with helium gas
Position the turbine in high altitudes to get higher wind speeds	Tower	Cable

- Use of blades and rotor to convert kinetic wind energy in rotational mechanical torque
- Position the turbine in high altitudes to get higher wind speeds
- Maintain the turbine in high altitudes

4.2.2. Step 2.2: Definition of Technical Solutions

Considering the functional architecture developed during the first phase, existing design concepts have been identified using Case-Based Reasoning approach (step 2.1) and then concretized as technical solutions. These technical solutions are presented in Table **5**.

Table **6** presents the technical solutions we defined and result from the process aiming to concretize the functional architecture of the subsystem. This search for technical solutions allows us defining solution candidates for two parts of the subsystem design problem:

- The first one related to the wind energy conversion to harness kinetic energy produced by the wind in mechanical energy. Three solutions were retained in this step: the bladed horizontal axis rotor, the vertical axis turbine and the high-altitude wind turbine.

- The second one aims to support the turbine in order to stand the turbine at a high height from the ground. Two solutions were obtained: the first one considers a rigid tower and the second one uses a cable.

4.2.3. Step 2.3: Optimization and Design of Subsystem Layouts

In this step, we aim designing layouts for the "Harness wind energy" function by combining the solution provided in Table **7**.

Table **7** presents the design structure matrix used to identify compatibilities between the different technical solutions. (Fig. **12**) shows how subsystem layouts can be defined by combining the solutions presented in the morphological matrix (Table **6**) and their compatibilities Table **7**.

[3] The autonomy time expresses how many time the cottage can be supplied without wind producing energy

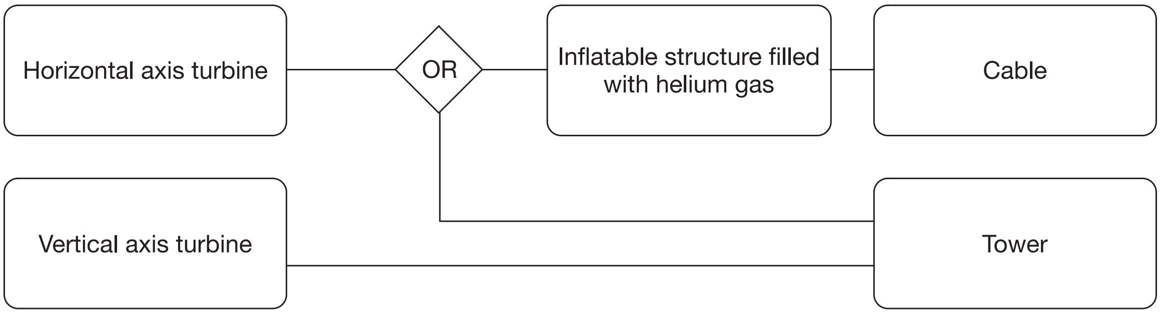

Fig. (12). Diagram showing connection rules between the different technical solutions considering their compatibilities.

Table 7. Design Structure Matrix (DSM) for "Harness wind energy" function.

Technical solutions		A	B	C	D	E
A	Horizontal axis rotor with blades		0	1	0	0
B	Vertical axis rotor with blades	0		0	0	0
C	Inflatable structure filled with helium gas	0	0		0	1
D	Tower	1	1	0		0
E	Cable	1	0	1	0	

Based on the morphological and the design structure matrices we identified three possible combinations:

- The use of a vertical axis turbine and a tower to raise the turbine;
- A horizontal axis turbine with a tower, like classical wind turbine structures.
- A horizontal axis turbine and an inflatable structure filled with gas connected to the ground by a cable. The helium gas is lighter than air and therefore allows to maintain the turbine in the air, eventually in high-altitude where the wind speed more important than on the ground floor.

4.3. Phase 3: Mechatronic System Integration and Optimization

Once subsystem layouts have been designed and optimized during the previous phase, these subsystems will now be integrated into mechatronic system layouts. Candidate mechatronic systems are then evaluate against the global design problem. Subsystem layouts resulting from phase 2 are integrated in candidate mechatronic solutions.

4.3.1. Step 3.1: Integrate Subsystem Layouts into Mechatronic System Layouts

The application of the second phase to the six sub-problems allowed us to define candidate solutions for each feature of the wind turbine. In this step, we aim to integrate the subsystem layouts defined in (Table **8**) in order to build architectures for the wind turbine.

Table 8. Candidate subsystem layouts for the several technical functions defined in FAST diagram (Fig. 11).

Technical functions		Subsystem layout 1	Subsystem layout 2	Subsystem layout 3
TF1	**Convert wind energy into mechanical energy**	Horizontal axis + tower	Vertical axis + tower	High-altitude wind turbine
TF2	**Adapt the torque/velocity**	Simple gearbox	Planetary gearbox	
TF3	**Convert into electricity**	Synchronous machine	Asynchronous machine	Asynchronous machine with hyper-synchronous cascade
TF4.1	**Adapt electricity**	Power inverter	Rectifier	Chopper
TF4.2	**Store electricity**	Batteries	Supercapacitors	
TF4.3	**Optimize supplied energy**	PI/PID Velocity controller	$H\infty$ controller	Maximum Power Point Tracker

In accordance with the objectives of the design problem, we first analyzed the compatibilities between the different technical solutions in order to express combination rules. (Table **9**) presents an excerpt of the Design Structure Matrix that summarizes this analysis. Based on matrices, we combined technical solutions according to their compatibilities in order to build candidate architectures for wind turbine layout Fig. **13**.

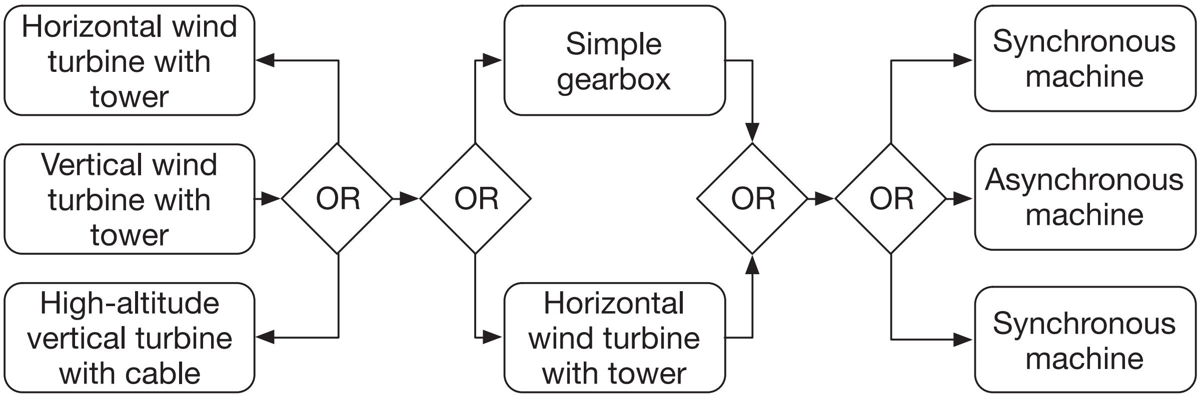

Fig. (13). Extract of wind turbine system architectures.

Table 9. Extract of the design structure matrix presenting compatibilities between the technical solutions.

	Subsystem layouts	A	B	C	E	F	G	H	I	J	K	L
A	Horizontal axis rotor with blades		0	0	1	1	1	0	0	0	0	0
B	High-Altitude wind turbine	0		0	1	1	1	0	0	0	0	0
C	Vertical axis rotor with blades	0	0		1	1	1	0	0	0	0	0
E	Planetary gearbox	1	1	1		1	1	0	0	0	0	0
F	Synchronous machine	0	0	0	0		0	1	1	0	0	0
G	Asynchronous machine with hyper-synchronous cascade	0	0	0	0	0		1	1	0	1	1
H	Power inverter	0	0	0	0	0	1		1	1	1	1
I	Chopper	0	0	0	0	0	1	1		1	1	1
J	Batteries	0	0	0	0	0	1	1	1		0	0
K	PI/PID controllers	0	0	0	0	0	1	1	1	0		1
L	Maximum Power Point Tracker	0	0	0	0	0	1	1	1	0	1	

4.3.2. Step 3.2: Identify Optimal Parameters of the Mechatronic System Layouts

This optimization process has been performed using ModeFrontier to solve the integration problem. (Fig. **14**) presents the results regarding the integration of the subsystems from the (Table **8**) into mechatronic solutions. These results have been obtained using NSGA-II optimization algorithm.

Fig. **14a** compares the mechanical power produced by the turbine and the blade radius. The colored area shows the solutions that can be considered to produce more than 1kW with blade radius varying between 1 and 3.5 meters. Three curves are displayed, one for each technical solution for the mechanical structure. The high-altitude rotor seems to be the solution that is the most powerful as the wind speed in high-altitude is more important and therefore produces more energy.

Fig. **14b** compares the centrifugal force against the blade radius. This force is very important while designing wind turbine. An important centrifugal force intensity may result of a dislocation of the blades from the rotor. This graph shows two groups of curves as this force moreover depends on the material weight. Increasing the blade radius would lead to an increase of the centrifugal force with a parabolic form.

Fig. **14c** evaluates the mechanical power produced by the turbine against the mass of the blades. This graph is strongly correlated with the graph shown in 15a as the mass depends from the blade radius but also with the density of the material used to manufacture the blades.

Fig. **14d** compares the mechanical power and the angular velocity of the blades. This figure shows that increasing the mechanical power produced implies a reduction of the angular velocity. The power efficiency is indeed maximized when the ratio is constant [44]. That means that if the blade radius is increasing, than the angular velocity should decrease to maintain a maximal efficiency.

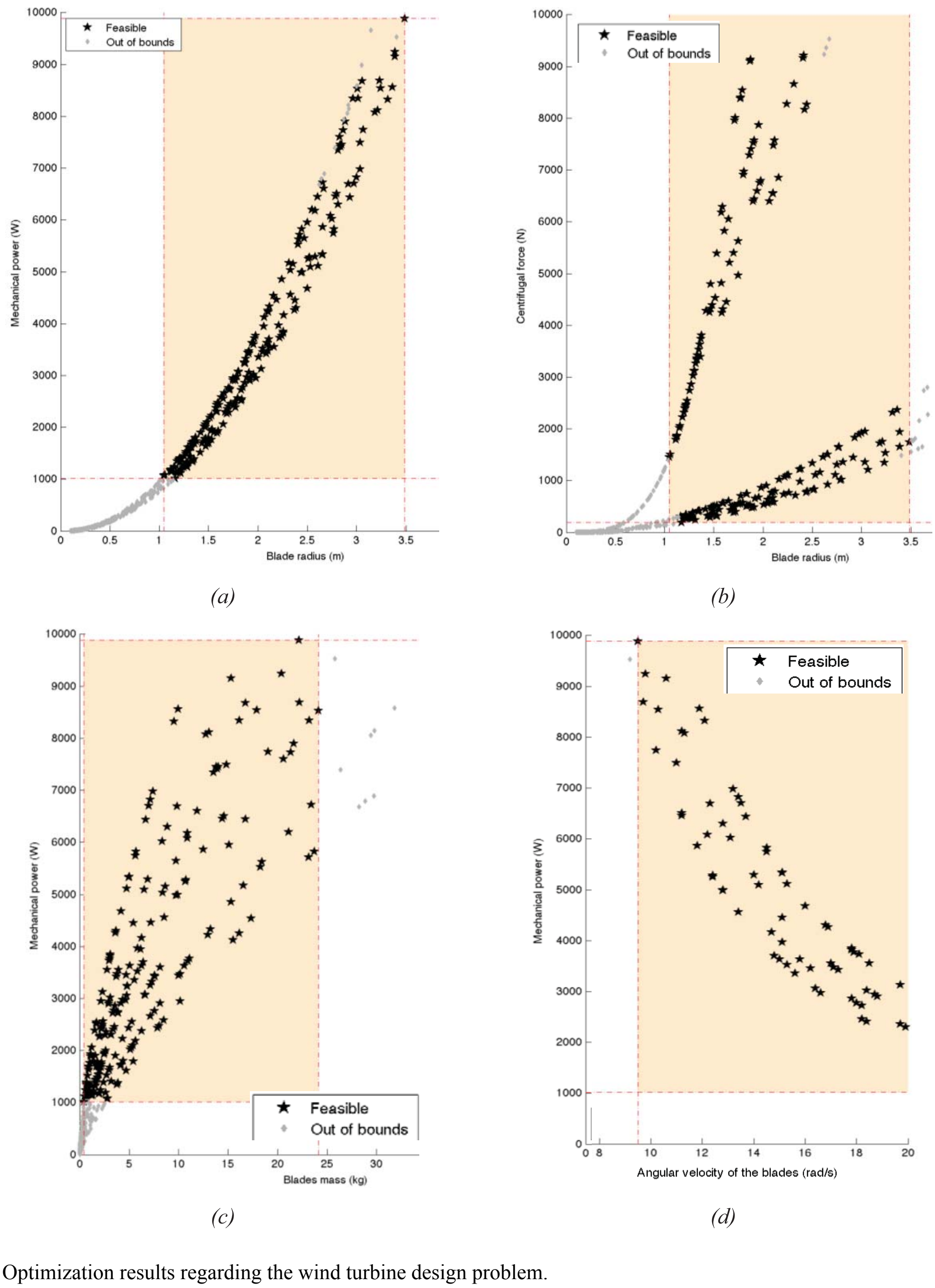

Fig. (14). Optimization results regarding the wind turbine design problem.

5. CONCLUSION AND OUTLOOK

In this paper, we presented a novel design methodology to better improve and optimize the functionalities and performances of mechatronic devices from the design stage. This methodology moreover focuses on the embodiment design process that aims to propose a mechatronic solution layout from a set of design concepts. This approach has then been successfully applied to the optimal design of a wind turbine system to autonomously supply a mountain cottage. The proposed approach needs to be characterized on complex mechatronic devices, such as unmanned aerial vehicles (UAV), and weaknesses of our approach need to be identified. This approach is however limited by technological advances in computer software to fully automate the proposed design process.

Future works will be conducted in the development of a specific software tool to increase the efficiency of the proposed approach and indexing solutions from existing solution bases available on the Internet and in patents. This extraction of knowledge can indeed help designer in developing more inventive products and integrating solutions from diverse technologies.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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Declared None.

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