A Design Approach Of Mechanical Assemblies Based On MBSE And CAD Models Interoperability

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Abstract

The technological development of the last decades have been able to push human to develop their needs, so a way to new demands were opened and this can lead to a complexity problem. Thereby, a good interoperability between the product design activities can lead to the possibility of ensuring a promising satisfaction to all requirements. However, the major problem is the enormous discontinuity between them. Indeed, each one treats the product from its point of view without recourse to the requirements defined by others. This paper is interested in the collaborative work that brings together the system engineer, who deals with the system from a global view, and the designer, who is a specialist in the detailed design, in order to validate requirements. A new methodology has been proposed to define the role of each one in the design process. This methodology focuses on the product development cycle from the analysis of needs to the validation phase. This obviously requires interoperability between the two domains of Model Based System Engineering (MBSE) and Computer Aided Design (CAD). Based on a pedal bicycle case study which is an industrial mechatronic product, the proposed methodology will be illustrated for validation and highlighting its advantages and limitations.

Introduction And Literature Review

Competitiveness in the market today requires manufacturers to produce products that tend towards perfection. This leads to increasingly precise requirements and it is the role of engineers to meet all of them to validate customer needs. Thus, interoperability between the multiple disciplines is sought in order to enhance the product quality and the time to market [1]. But the current problem is the discontinuity of communication between them. Indeed, every design actor works on his own data, methods and models, which can risk having products that lack consistency [2]. So, to tend to a perfect product, all the trades that contribute to its realization must work together. This will obviously minimizes the risk of error especially for systems that present a higher degree of complexity since communication between disciplines ensures good continuity of work.

Products of nowadays are the combination of different engineering disciplines such as mechanical, electrical, software engineering, etc. which increases the complexity and the cumbersome exchange of information [3]. This needs to ensure consistency between various engineering trades to get a final satisfactory product. Drave et al. aimed to improve the collaboration of experts in heterogeneous fields. They elaborated a Meta-model for the functional architectures of Cyber-Physical System (CPS) and developed a demonstration of how to code it as a System Modeling Language (SysML) profile. The proposed approach allows mechanical engineers to model these architectures in a way that promotes reuse and exploitation of innovative solutions [4]. Model Based System Engineering (MBSE) and Computer Aided Design (CAD) activities are among the trades that require interoperability to ensure a good consistency and requirements satisfaction. Indeed, the need to model mechanical assemblies design in the MBSE environment arises, which facilitates its understanding by system engineers. However, there is only few works that have addressed the communication problem between the two disciplines. In fact, each engineer works using his own methods, models and tools without relation with other actors, which generates an heterogeneity problem [5]. The heterogeneity problem between MBSE and CAD models has led to the development of research works. In the following section, a literature review on CAD and MBSE approaches and the interoperability between them will be presented.

1.1. Literature review on CAD approaches

To face the complexity problem of mechanical systems, several research works were developed. This will undoubtedly help to have simpler products not only in their understanding but also in their handling. For example, to deal with the problem of data transfer between physically distant designers, Shyamsundar et al. developed a tool to exchange assembly models facilitating data modifications [6]. The transfer of data between the different actors is interesting because it will help to analyze the product properly by ensuring the right compromise between cost, quality and time. Other researchers addressed the problem of determining the assembly steps in order to reduce assembly time. Melckenbeeck et al. developed a new approach to calculate feasibility scores for each assembly step in order to deduct the optimal Assembly or Disassembly Plan (AP/DP) for the final product [7]. In CAD domain, researchers also attach a great importance to assembly analysis because it has a great effect on the validation of product requirements. For example, the automatic estimation of the manufacturing costs of a part from the early stages of design is a trend that is beginning to integrate CAD software. This application is interesting because it makes it possible to optimize and reduce the manufacturing costs even before moving to the production phase. For certain CAD software, this approach has been recently integrated but still underdeveloped. It only applies to mechanical parts made from sheet metal or machined mechanical parts [8]. In the same context, Ghali et al. developed a new methodology for the allocation of tolerances. The objective is to integrate tolerance allocation into CAD models taking into account the functional requirements of the product which can facilitate its analyzing. In the proposed approach, the Failure Modes, Effects and Criticality Analysis method (FMECA) is used to allocate tolerances based on the manufacturing difficulties [9].

Besides the complexity of the 3D CAD design, there is also the complexity related to the generation of AP/DP which can also cause other difficulties in the understanding of designers work by other disciplines. From a CAD model, the AP/DP of a mechanism is determined in order to save time, validate or approve the design solution. More recent works were developed in this theme and has focused on the implementation of AP integrated into CAD systems. Ben Hadj et al. were interested in the implementation of a method to generate APs integrated to Solidworks© software as a Plug-in. In this work, the authors began by extracting data from the CAD model, and then, collision tests were carried out to automatically generate feasible APs. The developed method were tested on several industrial products and has shown its efficiency in generating feasible APs [10]. In the same context, Belhadj et al. developed a new approach based on the elimination of connection elements to have simpler APs. Then for each part a score is calculated in order to know which part should be assembled first. Finally a case-based reasoning algorithm is used for the insertion of all parts in the global AP [11]. Dini et al. developed an approach to find subassemblies and APs from a mathematical formulation of a mechanical product. The proposed approach is based on three matrices (interference, contact and connection) [12]. For heavy machines and in order to better analyze the operator safety and the mounting tools workspaces, Bedeoui et al. proposed an approach to generate the most optimal APs based on the stability of components during assembly operations [13].

As for the AP generation, other researchers were interested in the DP generation to facilitate the complexity of mechanical systems. Li et al. proposed an integrated approach to generate disassembly constraints by directly using information from the CAD model which allows designers to assess the current design for its disassembly properties [14]. In the same context, Belhadj et al. were interested in the determination of sub-assemblies, especially for mechanisms with a high number of parts. The proposed approach automatically identifies subassemblies from a geometric model of a mechanical assembly and determines feasible DPs [15, 16]. The authors developed a new method for parallel disassembly in order to improve the design quality of the product by taking into account a set of evaluation parameters such as the recyclability rate and the total disassembly time of the product [17]. Morato et al. proposed an AP approach by generating the potential layers of disassembly. This approach is based on motion planning and spatial clustering to generate sets of parts that have mobility between them [18].

1.2. Literature review on MBSE approaches

According to the literature on MBSE approaches, new research works have investigated the development of this domain to facilitate the conceptual phase of complex systems. In order to facilitate the understanding of highly complex systems, Mhenni et al. developed a SysML methodology dedicated to mechatronic systems which is divided into two parts: the first deals with the system from an external point of view by providing all the requirements to be satisfied, and the other illustrates in a detailed way the internal architecture of the system [19]. As part of the MBSE development and especially to improve languages used by system engineers, Noten et al. presented some experiences and limitations encountered when applying and customizing SysML. An industrial use case is designed by a multidisciplinary team through several companies [20]. These developments can lead to the knowledge expansion which offers the opportunity to fulfill the steps of verification and validation of the product requirements. In the same topic, Gardan et al. provided conceptual models that improve the MBSE to take into account Knowledge Management (KM). Using existing SysML diagrams, the proposed approach formulates a decision model that complements existing methods by offering KM solutions focused on organizational approaches. The fulfillment of requirements relies on this conceptual approach to aid in the decision-making process [21]. Considering its important role, several research works were based on the application of system engineering to obtain a better quality of products. Based on the application of MBSE using MADe and MagicDraw Modeling Tools, Odita et al. verified the reliability, risk and safety of aerospace components [22]. Other researchers use profiles to model specific aspects which aim to enrich SysML with external information and it can give the opportunity to model external problems in the MBSE environment. Pop et al. proposed a Unified Modeling Language (UML) profile for Modelica language [23]. Moreover, Paredis et al. suggested another profile that connect SysML and Modelica [24]. A new profile named “SafeSysE” was proposed to facilitate the extension of system models with some safety properties [25]. Moreover, Brahmi et al. developed a SysML profile for the description and the analysis of mechanical assemblies which can be used in the MBSE environment in order to describe the designer's work. The proposed profile can enhance the continuity between the data generated by the two actors by checking and validating the design solution [2].

1.3. Literature review on interoperability and collaborative works

In recent years, researchers have been able to feel the real need for communication between the different disciplines in order to ensure all the requirements. They have been able to know that to ensure this exchange and interoperability of data, standard means of communication are necessary. For this reason, researchers worked on extracting and collecting data based on CAD models of assemblies in order to have information related to the mechanical parts allowing its reuse in other fields. Gouta et al. proposed a tool for extracting and collecting data from a CAD model of an assembly. These data are saved in Excel or Matlab format. The developed tool, called Computer Aided Design Laboratory (CADLAB), constitutes a link between the CAD system and Computer Aided Engineering (CAE) applications [26]. Kleiner et al. combined the functional, logical and physical requirements in a single tool integrated in CATIA-V6©. This approach allows significant collaboration between different engineering disciplines [27]. Other studies were carried out to highlight the importance of integrating different fields. Mauborgne et al. developed an MBSE approach to allow the evolution of the preliminary risk analysis method in order to meet the requirements for the automotive sector [28]. The problem of interoperability affects several fields such as the conceptual modeling. In this context, Tolk and Muguira presented a general model dealing with different levels of conceptual interoperability [29]. Zeng discussed a new approach that enables to achieve interoperability, as demonstrated by standards and best practices, projects and products in the broad area of knowledge organization [30].

1.4. Outcomes of the literature review

According to the literature review discussed previously, it can be noted that:

- Several research works are concerned in the development of CAD domain, 3D design and the implementation of computer tools to reduce the complexity of mechanical assemblies.
- Researchers in the system engineering environment developed new methodologies in order to facilitate the use of system engineering tools for the benefit of other domains.
- The two fields which are MBSE and CAD evolve but each one apart.
- A problem of discontinuity of communication between the two domains appears which favors the risk of nonconformities of the product design with the requirements of the customer.

In this paper, the proposed approach aims to solve the problem of collaboration between the system engineer who has a global view on the product and the designer who is a CAD specialist. The objective is to ensure the satisfaction of all the product requirements and to analyze and validate the proposed design solution. The proposed methodology is detailed and validated using an illustrative industrial example which is a pedal bicycle.

Proposed Approach

To achieve all the user needs, a compromise between the system engineer and the designer is required. Figure 1 presents the proposed methodology which illustrates the collaborative work between them. The outline of the proposed approach is decomposed into three main parts as follows:

- An MBSE preliminary analysis: in this step, a global study of the product from a functional point of view is performed by the system engineer.
- CAD development: in this step, the designer proposes and analyzes the 3D CAD design of the proposed solution.
- MBSE enrichment and validation: in this step a checking if the proposed design solution is satisfactory is done by testing the concordance of the collaborative CAD-MBSE work to the customer requirements.

For the validation of the collaborative methodology, an illustrative industrial example designed and manufactured by the company *Pedalite*. The treated example is a luminous pedal named *KPL200* and presented in Fig. 2. The principle is simple, efficient and innovative: while pedaling, a small generator integrated into each pedal produces current and powers the flashing lights. The produced excess energy is stored and will be restored when the cyclist is not pedaling (downhill, at a stop, etc.). Battery life is around 5 minutes. The KPL200 pedal increases the visibility of cyclists and is with free maintenance: no batteries, no wires, no moving parts and no risk of breakdown. They are therefore particularly reassuring for parents who know that their children remain visible, even if their dynamo light fails. In this paper, the design process of the KPL200 pedal is detailed using the proposed approach.

2.1. The MBSE preliminary analysis step

i. Need analysis

With the technological development, customer requirements still increase. Indeed, in order to develop competitive products, understanding the entire customer's needs is a decisive matter for the rest of engineers work. So before embarking on product design which can lead to sometimes expensive and unwise solutions, it is necessary to dissect and analyze all of these needs. This is the stage where the system engineer is invited to study needs and to translate them into algorithms or in textual format that enables to continuously improve the understanding of the system by other actors. This is the first step that opens the chance to decipher all the necessities. For the treated example, the primary need from the pedal is to improve road safety by increasing the visibility of cyclists at night even under difficult weather conditions.

ii. Functional analysis

After analyzing customer needs, the second fundamental step is the definition of the functional requirements. These requirements are the result of a customer request that comes forward with imperfect information. He tries to explain his needs to the system engineer which is responsible for dissecting them in a specification and describing them in forms of actions and conditions to be satisfied by the final product. This description need to be complete, consistent and have a very clear structure in order to be understandable during the validation phase. This step is one of the most difficult one since it brings together the different actions to be satisfied, especially since the problem is not well formalized yet. For this, the system engineer uses an interface dedicated to defining requirements (SysML requirement diagram) to summarize the in-depth of his work. Each requirement block contains a unique name, a persistent identifier, and a text that briefly and generally describes the purpose of the requirement. It is mentioned that during this step there is a part of the system requirements which is devoted to the analysis of the product design. For the treated example, the functional requirement diagram is presented in Fig. 3. It details the requirements related to the transmission of the mechanical energy supplied by the cyclist to the crank-set of the bicycle.

iii. Initial assembly structure

The system engineer plays the role of an orchestra conductor ensuring multidisciplinary work between several jobs. Considering that he is not a specialist in a particular field, including mechanics, and that he only has a global vision of the system to be designed, the design of the mechanical assembly is allocated to a specialist in CAD. Therefore, during this step and after studying the system from a functional point of view, the system engineer can propose the initial structure of the assembly. This structure basically contains the parts which are essential in the functioning of the system and it can be modeled in a block definition diagram “bdd” from SysML. At this stage this diagram is used to describe the external architecture of the mechanism in a rough way. The building blocks of the diagram contain the name, attributes of the components, and are linked together by composition links. As represented in Fig. 4, the initial structure of the treated example can be composed of five essential parts which are: a pedal body and a pedal axis used to transmit the mechanical energy supplied by the cyclist during pedaling; a double intermediate wheel which multiply axis rotation; a generator for converting kinetic energy into electrical energy to have light flashes and an integrated circuit used to store the surplus of energy produced.

iv. Allocation and traceability

The traceability step has a major importance in improving the quality of the assembly. Through this step, the system engineer is invited to allocate each block of the assembly structure to the requirement to meet. The modifications that will be executed on any of the requirements will automatically influence the assembly blocks. Thus, the link between requirements and assembly components will be forged at this stage. This step is used to ensure the consistency of the solutions and to check not only that the proposed solution is good but that it is also the best while taking into account the good compromise between the proposed solution and the suggested requirements. For the treated example, Fig. 5 represents the allocations related to the part « pedal body ».

v. MBSE data generation

Once the preliminary analysis of the different MBSE steps is developed, the MBSE data generation phase can begin. The system engineer needs to represent his work through a structured model for the benefit of the CAD designer. To meet this need, the Extensible Markup Language format (XML), which is a simple, intelligible and coherent file, can be used. In this work, the XML file is generated automatically using an implemented *macro* which is developed in order to allow the standard exchange between the two fields. The resulting file is composed of three blocks. The first block contains all the functional requirements, ordered by the system engineer during the functional analysis stage. The second block includes the initial structure of the assembly. The third block contains allocations between components and requirements. Figure 6 presents the XML file of the treated example resulting from the generation of the MBSE data.

2.2 CAD development step

i. 3D CAD design

Once detailing the system from a functional and technical point of view and traducing the content of the work in an XML file, the 3D CAD design step can begin. The resulting file is sent to the designer in order to create the 3D CAD design solution. This will avoid design errors from the beginning when creating perfectly optimized parts, thanks in particular to the parametric functions and to the possibilities of simulations offered by CAD software. This will obviously help to avoid the need for multiple prototypes and tests. Thus, during this step, the designer is invited to create the solution based on the XML file generated by the system engineer. The designer details all the assembly components and constraints between them. The 3D CAD solution for the treated example, composed of 29 parts, is presented in Fig. 7. Table 1 illustrates the nomenclature of the proposed solution as well as the assembly time (At).

Tableau 1: Pedal nomenclature

Rep	item	Nb	Rep	Item	Nb
1	Pedal body	1	12	Screw	1
2	Pedal axis	1	13	Contact	2
3	Sealing ring	1	14	Electronic card	1
4	Bearing	2	15	Mechanical belt	1
5	spacer	1	16	Insert	2
6	Reflector cover	2	17	Inner cover	1
7	Reflector	2	18	Outer cover	1
8	CHC screw	2	19	Engine body	1
9	Generator	1	20	Motor wheel 1	2
10	Connector	1	21	Motor wheel 2	1
11	Bearing bracket	1	22	Motor cover	1

ii. Assembly analysis

Once the 3D design solution is performed and before returning an assembly design report, the proposed design solution should be evaluated to perceive if there would be any changes before continuing the collaborative work between CAD and MBSE engineers. In this work, a set of evaluation metrics are used to assess the assembly. These metrics are as follow: the maximum number of parts, the total assembly time (TAT), the assembly quality and the AP/DP plans which undoubtedly influence the efficiency of the design solution. It is noticed that, the evaluation report, based on the previously cited metrics, of the design solution can help the system engineer in the validation of the proposed solution. These metrics are detailed in the following section.

- **Maximum number of parts**

Using this metric, the designer need to analyze the assembly by checking if the total number of parts is optimal or can be reduced. The proposed metric is based on a procedure which tries to minimize the total number of parts. Consequently, the assembly design is simplified and the production costs are reduced. According to Boothroyd, the optimal number of parts in the assembly design can be calculated using a procedure based on the answer to four main questions [31]:

1. Is the part a base?
2. Is there a functional relative movement between the part and the others already assembled?
3. Does the part have to be made of different materials or be isolated from other parts already assembled?
4. Does the part need to be separated from other parts in order to allow assembly or disassembly?

For each part of the assembly, if the answer to the four questions is "no", the considered part is not required and can be eliminated from the assembly design. Else, the part must be retained and considered as a required one. Consequently, the sum of the required parts constitutes the minimum number (N_{min}) that the assembly design must have to satisfy requirements. For the treated example and based on this procedure, the Nmin of parts is 29 parts. Taking into account the requirements of the system engineer proposed in the functional analysis stage, this value can be accepted.

- **Total assembly time (TAT)**

To assess the design quality, the assembly time is a significant metric. Indeed, a long assembly time minimizes its quality. According to Boothroyd, experimental tables are used for the calculation of the handling and the insertion time of each part during the assembly process[32]. For the treated example and based on this methodology, the TAT is calculated and estimated to 141 seconds. It is noticed that the system engineering requirement for the maximum value of the TAT is 200s which is higher than the TAT of the proposed solution. Consequently, based on the TAT metric, the proposed design solution is satisfactory.

- **Assembly efficiency (AE)**

The assembly efficiency (AE) metric can estimate if the proposed design can be accepted or not according to a predefined threshold. The AE can be calculated using the following formula:

$$AE\ (\%) = \frac{\mathrm{T_{min}}.N_{min}}{\mathrm{TAT}}\ .100 \qquad (1)$$

Where:

- T_{min}: Minimum assembly time in the assembly line of the industry.
- N_{min} : Minimum theoretical number of parts.
- *TAT* : Total Assembly Time of the product.

For the treated example, the AE is obtained as follows:

$$AE = \frac{3*29}{141}\ .100 = 61\%$$

For the system engineering requirement, the minimum value of the AE is equal to 50%. Consequently, the proposed design, having an AE = 61%, is considered as a satisfactory solution.

- **Generation of Assembly and Disassembly plans (AP/DP)**

Determining the assembly and disassembly plans (AP/DP) is an important indicator to evaluate a design solution. In fact, choosing the wrong AP/DP can lead to a significant loss of time and money. The generation of feasible AP/DP is performed according to Ben Hadj et al. approach [11]. First, and to have a simpler AP/DP, a procedure of elimination of connection elements is done. Then, for each part, a score is calculated in order to know which part should be assembled first. Finally a case-based reasoning algorithm is used for the insertion of all parts in the global AP. By a similar reasoning the DP can be generated. The AP/DP plans of the treated example are shown in Fig. 8 and Fig. 9.

iii. CAD data generation

Once the evaluation of the proposed design is performed using the previously detailed metrics, a design report is generated and exported to the system engineer using a simple and easy format. Indeed the exported report ensures the checking and validation of the design solution by testing the satisfaction of the requirements specified by the system engineer.

Similar to the XML-MBSE generation, CAD data coupled to design metrics are also generated in an XML format where the resulting file summarizes the designer work. The resulting XML file contains all the data related to the parts attributes, such as: name, size, volume, weight and At. As well as the data related to the assembly such as: optimal number of parts, TAT and AE.

2.3 MBSE enrichment and validation

i. Assembly architecture updated

At this stage, all the assembly parts are known and detailed, which allows the system engineer to enrich and update the assembly architecture initially proposed. The generation of the new structure becomes easier thanks to the XML file received from the CAD environment. Consequently, a new enriched structure is modeled in a « bdd » which contains new information that comes to enrich the structure of the assembly initially proposed by the system engineer. For the treated example, the enriched structure of the assembly and a zoom on a part are presented in Fig. 10. In this figure, the pedal assembly is composed of five sub-assemblies. For example, the « pedal axis » sub-assembly is composed of a part named “axis” which is defined by a set of attributes such as the name, the surface, the handling time of the part, etc.

In order to detail the internal composition of each part which allows a better understanding of the assembly, an internal block diagram «ibd» is introduced. This diagram enriches the content of the «bdd» by adding the connection links between parts. For the validation example, the assembly architecture is presented in Fig. 11.

ii. Geometrical requirement definition

A mechanical assembly is a set of parts connected to each other by mechanical links. These connections can only be perfect if the parts in contact meet all the geometric requirements. After the design solution, new geometrical requirements will appear and must be satisfied. During this step, the system engineer will represent all the requirements that the mechanical parts must meet. The XML file received from CAD domain which details the relative information to subsequently test their satisfaction is used for this step.

Since mechanical assemblies contain a large number of standard parts whose number is generally more important compared to non-standard ones, their geometrical requirements, known in advance, are modeled in a SysML requirement diagram. This procedure can save time and reduce the work of the system engineer when representing the geometrical requirements of the assembly. The geometrical requirements of standard components and a zoom on only one part which is the pad are presented in Fig. 12. Thus, to model all the geometrical requirements of the parts constituting the assembly, the algorithm shown in Fig. 13 is proposed. The system engineer firstly identifies all the assembly parts and then selects a single component. If the chosen one is a standard component then its geometrical requirements are directly collected from the SysML requirement diagram previously illustrated. Otherwise, new requirements are to be defined based on the designer work. This step needs to be repeated until all the parts of the assembly are treated.

iii. Validation

The validation stage is the final step of the interoperability exchange between the systems engineer and the CAD designer. During this step, the system engineer is asked to test whether all of the predetermined requirements have been validated. Therefore, a documented proof is established in order to check if the designed solution is accepted or not. This step consists of grouping together the requirements collected from the MBSE environment with the mechanical parts collected from the CAD domain. The two aspects are structured in a SysML allocation matrix that helps providing an efficient way to communicate and interconnect elements from different domains. The role of the allocation matrix is to allocate relations of satisfaction between each requirement (from MBSE domain) with the assembly parts (from CAD domain).To deal with this, the system engineer is invited to check all the requirements one by one. He tests whether the requirement has been met by the appropriate mechanical part or not. Moreover, the required metrics of the design solution which are introduced in the "Functional analysis" phase will be compared to the values found by calculation from the proposed solution which will facilitate their satisfaction test. This will obviously make it possible to deduce whether the proposed design solution is optimal and adequate or not. Indeed, if all the system requirements have been verified and validated by the mechanical parts, the design solution is validated. Otherwise, a report will be sent back to the CAD designer that contains requirements which are not satisfied in order to make the appropriate modifications on the assembly design. The allocation matrix of the 3D CAD design of the pedal mechanism and a zoom on the validation of the assembly design analysis indicators part are presented in Fig. 14.

Discussion

The problem of communication discontinuity between MBSE and CAD domains can lead to a non-conforming product with requirements. The proposed approach presents an interoperability process between the system engineer and the CAD designer. A standard exchange format is available for each of them in order to facilitate the comprehensibility of the developed work. This will avoid not only the discontinuity problems but also helps the system engineer to translate the assembly data into SysML format. The proposed approach considers some evaluating metrics such as the feasible AP/DP, the TAT and AE which allow the requirements validation step. Finally, the system engineer should judge if the design solution is adequate or not according to the system requirements.

Conclusion And Future Work

To achieve customer satisfaction, communication and exchange between different disciplines plays a key role in product validation. This exchange can sometimes be difficult given the lack of standard means of communication. This paper proposes a methodology that facilitates the MBSE-CAD collaboration. Between the two disciplines, each engineer develop his own work and the data exchange is allowed through files in XML format, which implies an easy interconnection. This involves a standard exchange language between the two domains that finally facilitate the validation step of the designed solution. Using a pedal bicycle example, the methodology was detailed.

As a future work, the developed approach can be improved by favoring the automated check of the validation step.

Abbreviations

CAD: Computer Aided Design

MBSE: Model Based System Engineering

CPS: Cyber-Physical System

SysML: System Modeling Language

DFA: Design For Assembly

XML: Extensible Markup Language

ibd: Internal block diagram

bdd: Block definition diagram

AP: Assembly Plan

DP: Disassembly Plan

KM: Knowledge Management

At: Assembly time

TAT: Total Assembly Time

Declarations

Ethical Approval: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to Participate: The authors declare that there is no objection.

Consent to Publish: The authors declare that there is no objection.

Authors Contributions: In this paper, A CAD based tolerance allocation tool based on manufacturing difficulty quantification, quality loss and manufacturing costs is proposed.

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Availability of data and materials: The authors declare that all relevant data are within the paper and its supporting information file.

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Figures

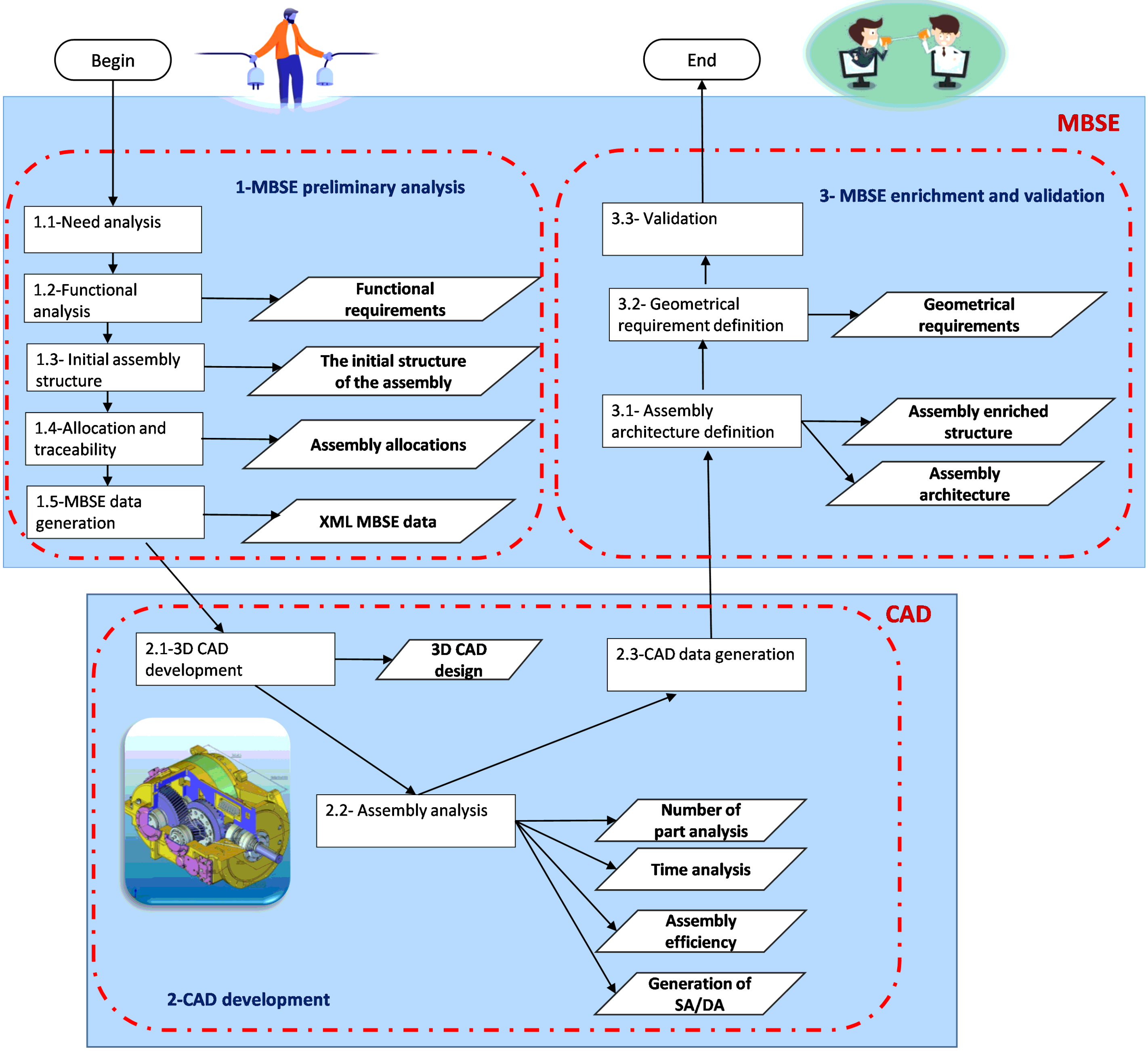

Figure 1

Proposed approach

Figure 2

Bicycle pedal with flashing LED lights

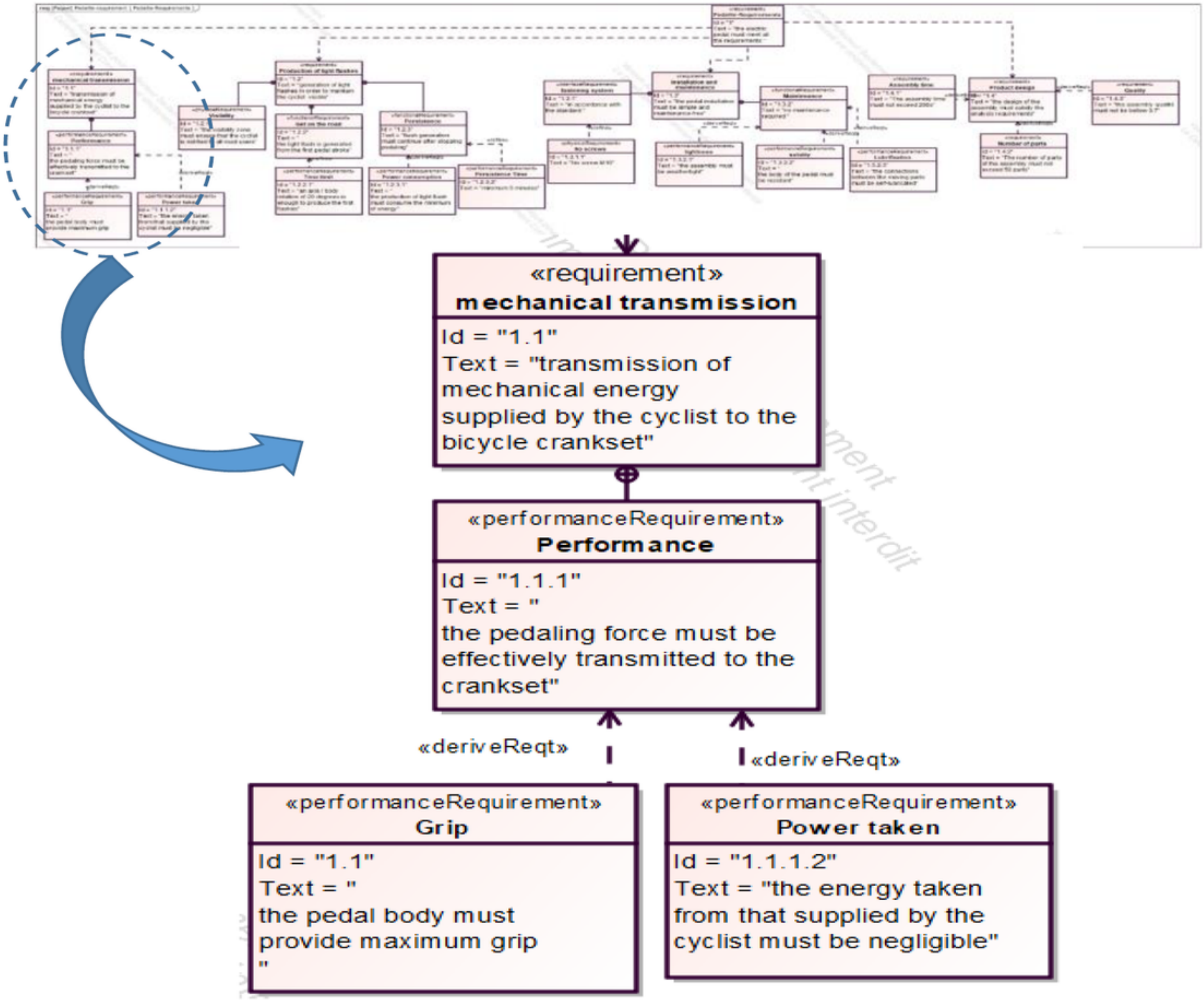

Figure 3

Pedal requirements diagram

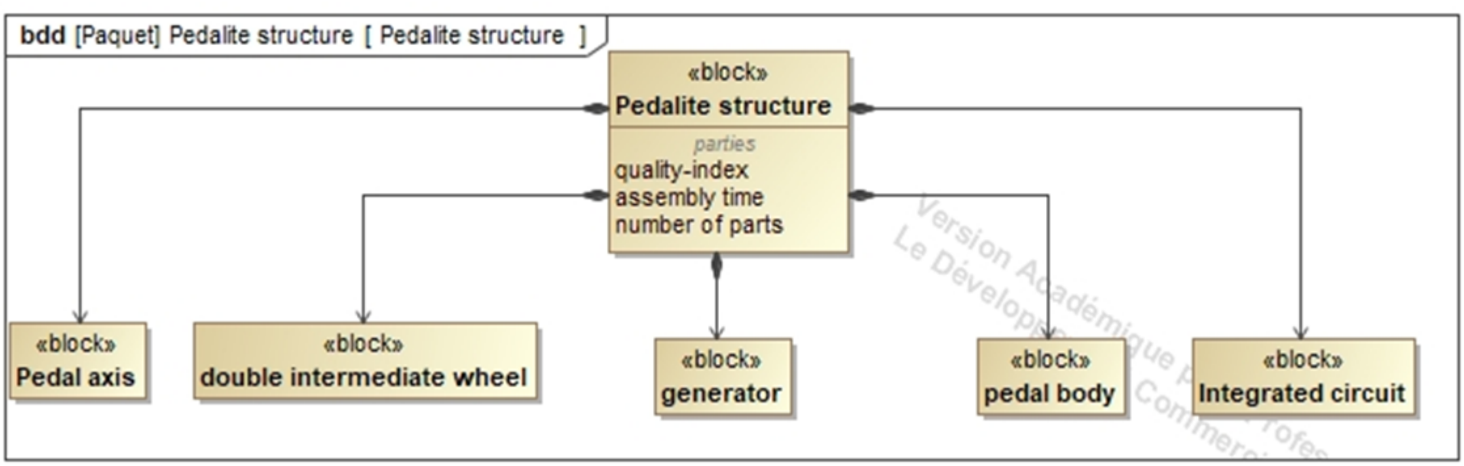

Figure 4

Initial structure of the pedal

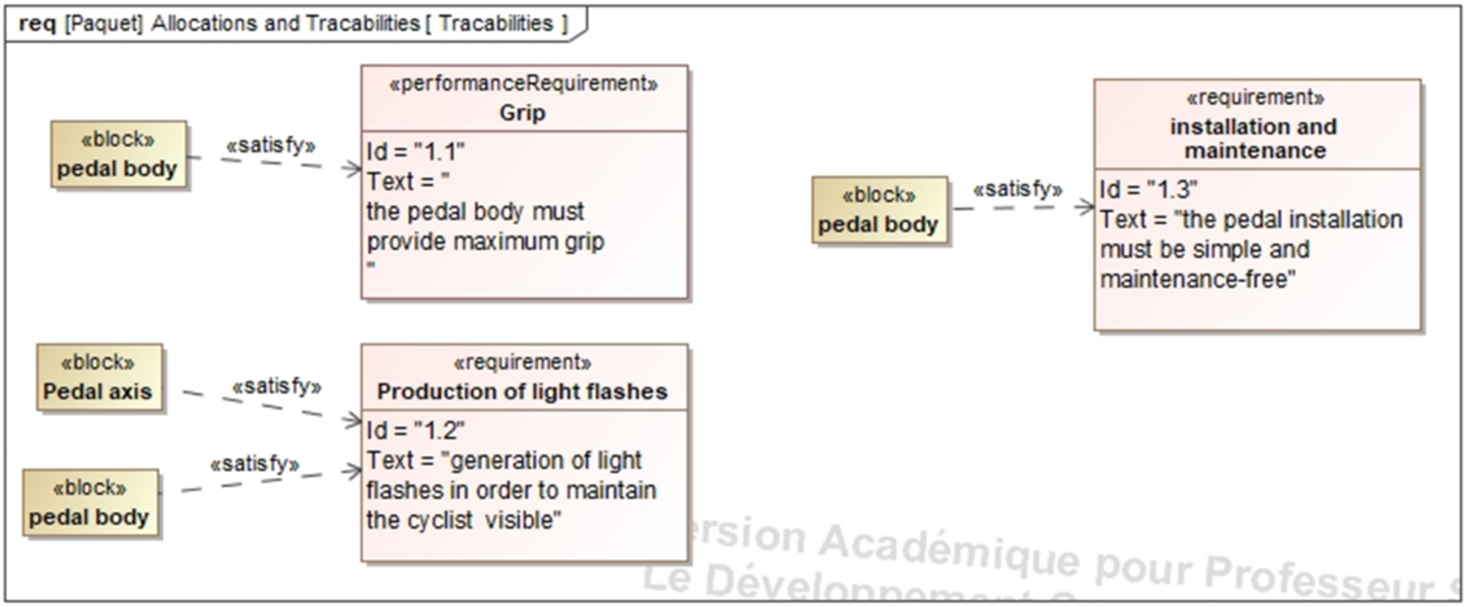

Figure 5

Allocation and traceability of the pedal

```
  <?xml version="1.0"?>
- <Pedalite>
  - <pedalite-requirements>
    - <mechanical-transmission>
         Transmission of mechanical energy supplied by the cyclist to the bicycle crankset
      - <Performance>
           The pedaling force must be effectively transmitted to the crankset
           <Grip>The pedal body must provide maximum grip </Grip>
           <Power-Taken>The energy taken from that supplied by the cyclist must be negligible</Power-Taken>
        </Performance>
      </mechanical-transmission>
    - <Production-of-light-flashes>
         generation of light flashes in order to maintain the cyclist visible
         <Visibility>the visibility zone must ensure that the cyclist is notified to all road users</Visibility>
      - <Get-on-the-road>
           The light flash is generated from the first pedal stroke
           <Time-Limit>an axis / body rotation of 20 degrees is enough to produce the first flashes</Time-Limit>
        </Get-on-the-road>
      - <Persistence>
           flash generation must continue after stopping pedaling
           <Power-consumption> the production of light flash must consume the minimum of energy</Power-consumption>
           <Persistence-time>minimum 5 minutes</Persistence-time>
        </Persistence>
      </Production-of-light-flashes>
    - <Installation-and-maintenance>
         the pedal installation must be simple and maintenance-free
      - <Fastening-systems>
           in accordance with the standard
           <No-screws>No screw M10</No-screws>
        </Fastening-systems>
      - <Maintenance>
           no maintenance required
           <Tightness>the assembly must be weathertight</Tightness>
           <Solidity> the body of the pedal must be resistant</Solidity>
           <Lubrification>the connections between the moving parts must be self-lubricated</Lubrification>
        </Maintenance>
      </Installation-and-maintenance>
    - <Product-design>
         The design of the assembly must satisfy all te analysis requirements
         <Assembly-time>The assembly time must not exceed 200s </Assembly-time>
         <Number-of-parts>The number of parts of the assembly must not exceed 50 parts </Number-of-parts>
         <Quality>The assembly quality must not be bellow 0.7</Quality>
      </Product-design>
    </pedalite-requirements>
  - <pedalite-intinal-structure>
       <pedal-axis/>
       <double-intermediate-wheel/>
       <generator/>
       <pedal-body/>
       <integrated-circuit/>
    </pedalite-intinal-structure>
  - <allocaton-and-tracability>
       <pedal-body>the pedal body must provide maximum grip </pedal-body>
       <pedal-body>generation of light flashes in order to maintain the cyclist visible</pedal-body>
       <pedal-body>the pedal installation must be simple and maintenance-free</pedal-body>
    </allocaton-and-tracability>
</Pedalite>
```


Figure 6

XML-MBSE generation file

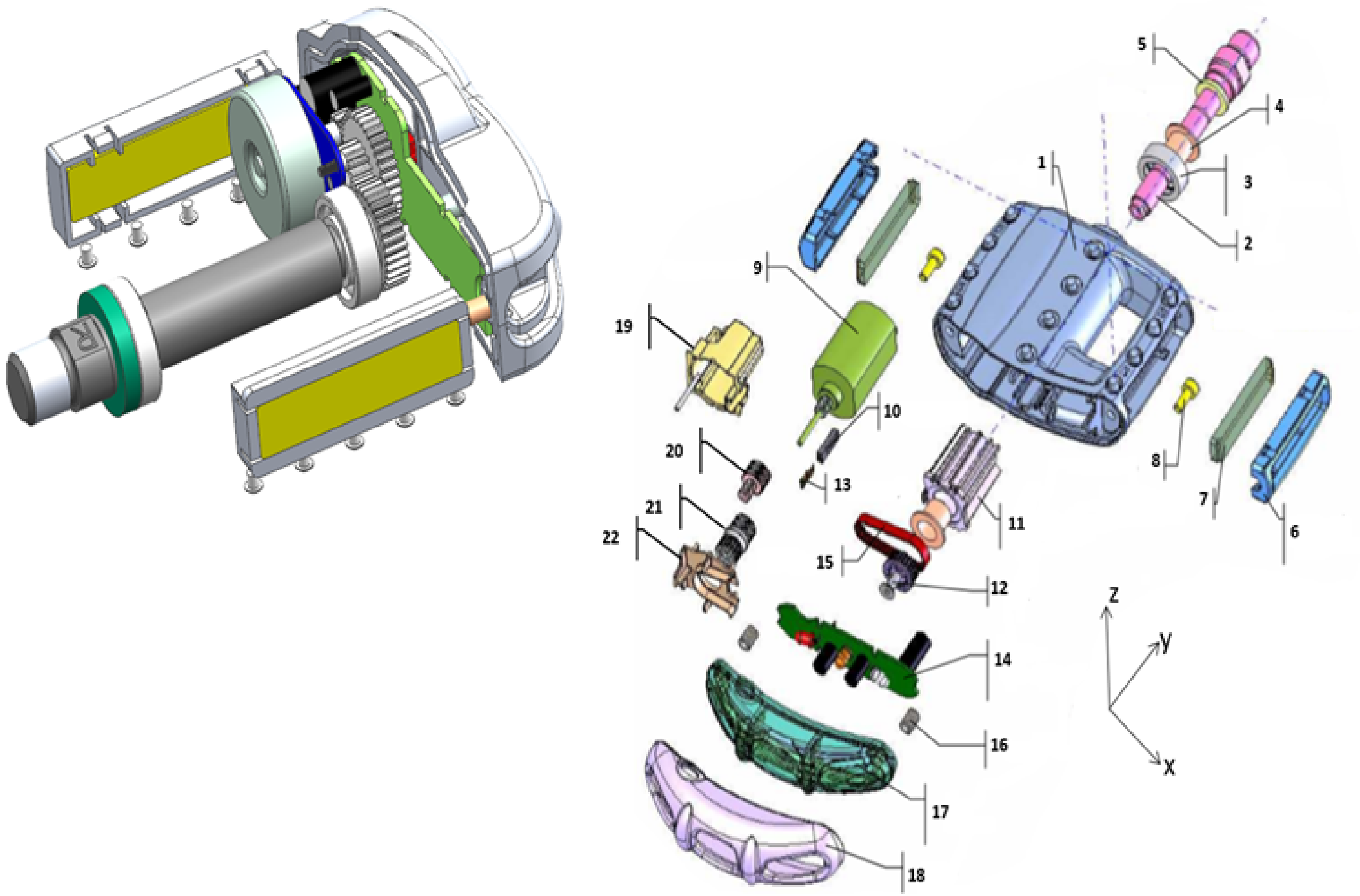

Figure 7

CAD and exploded design view of the pedal bicycle

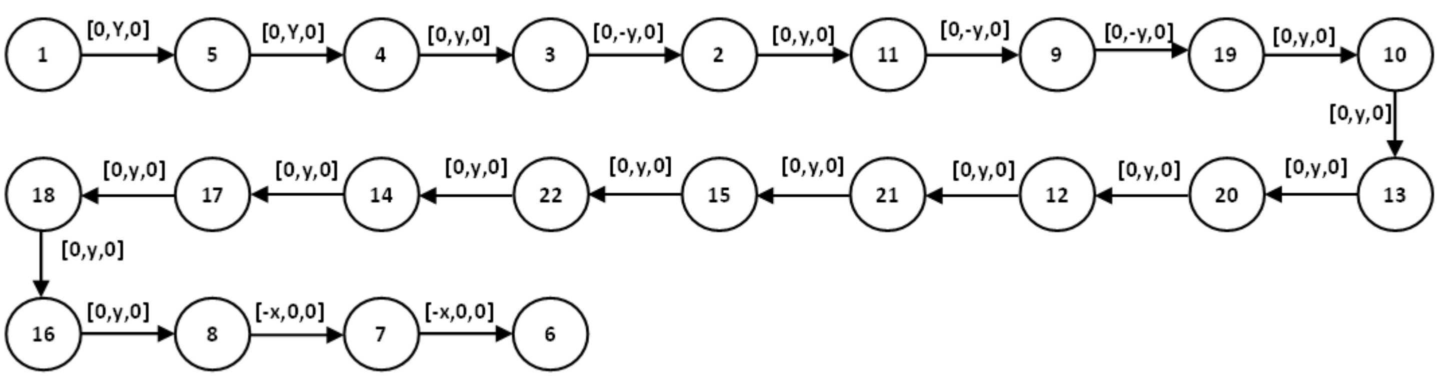

Figure 8

Pedal assembly plan

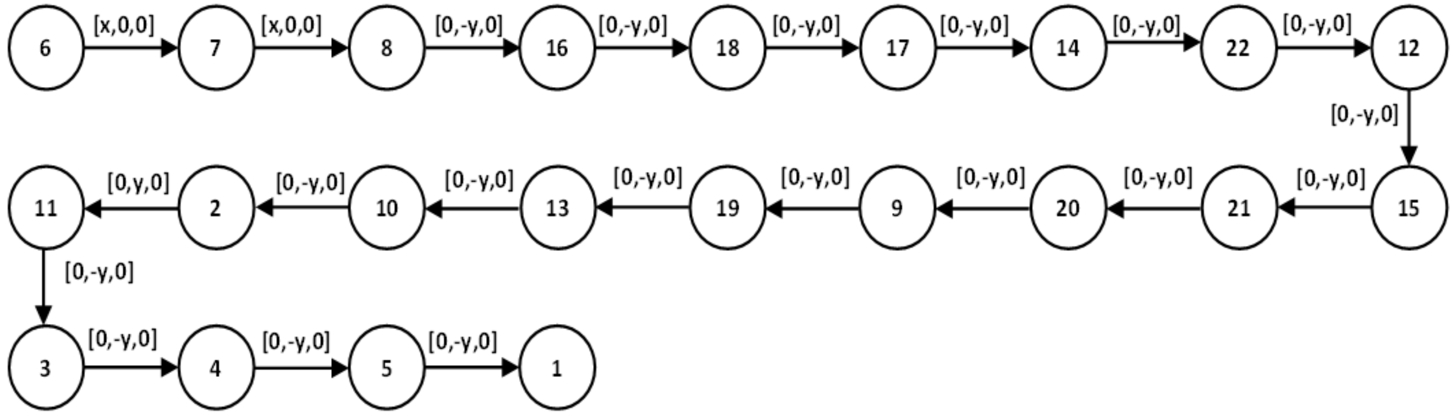

Figure 9

Pedal disassembly plan

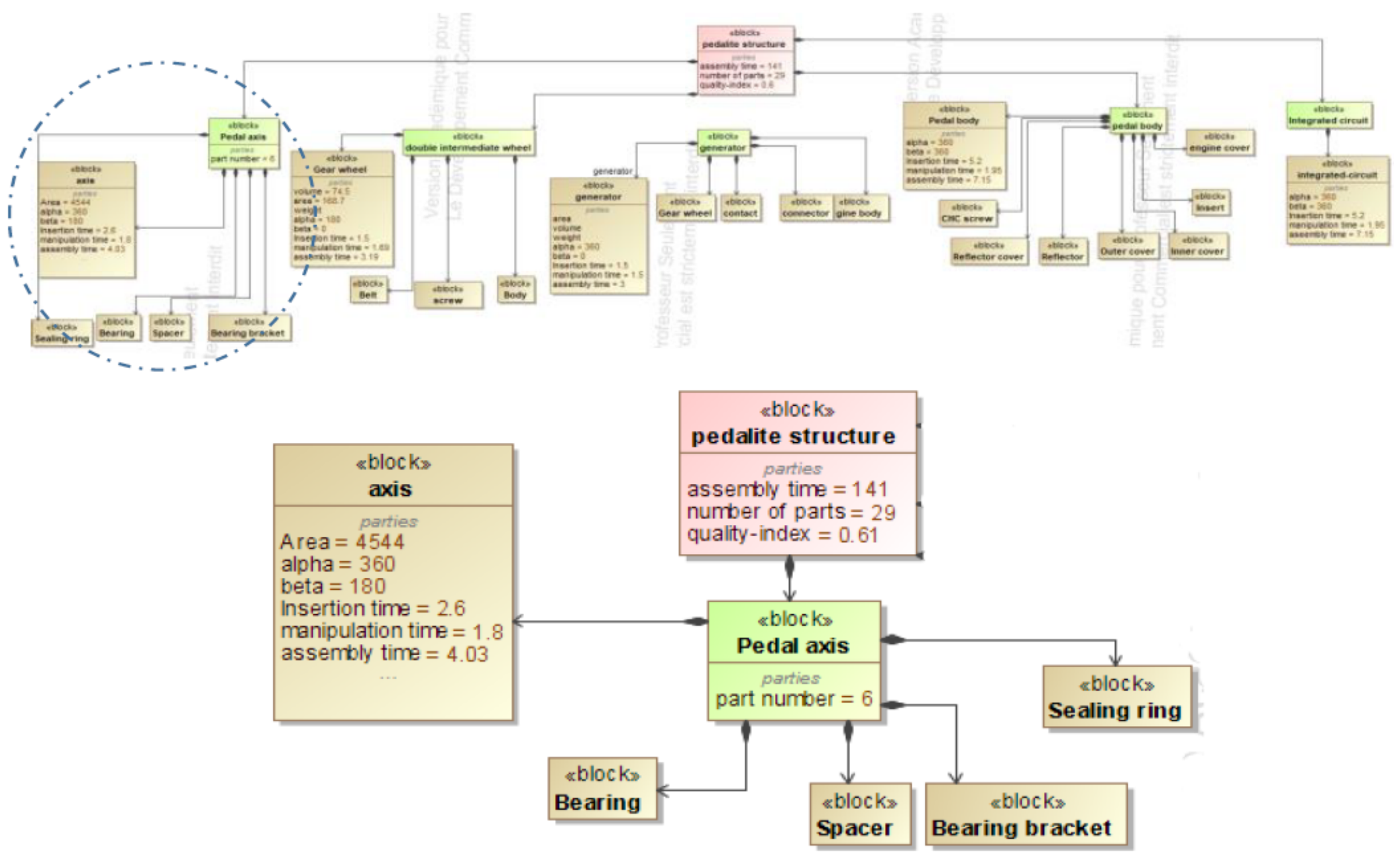

Figure 10

Enriched structure of the pedal in the MBSE environment

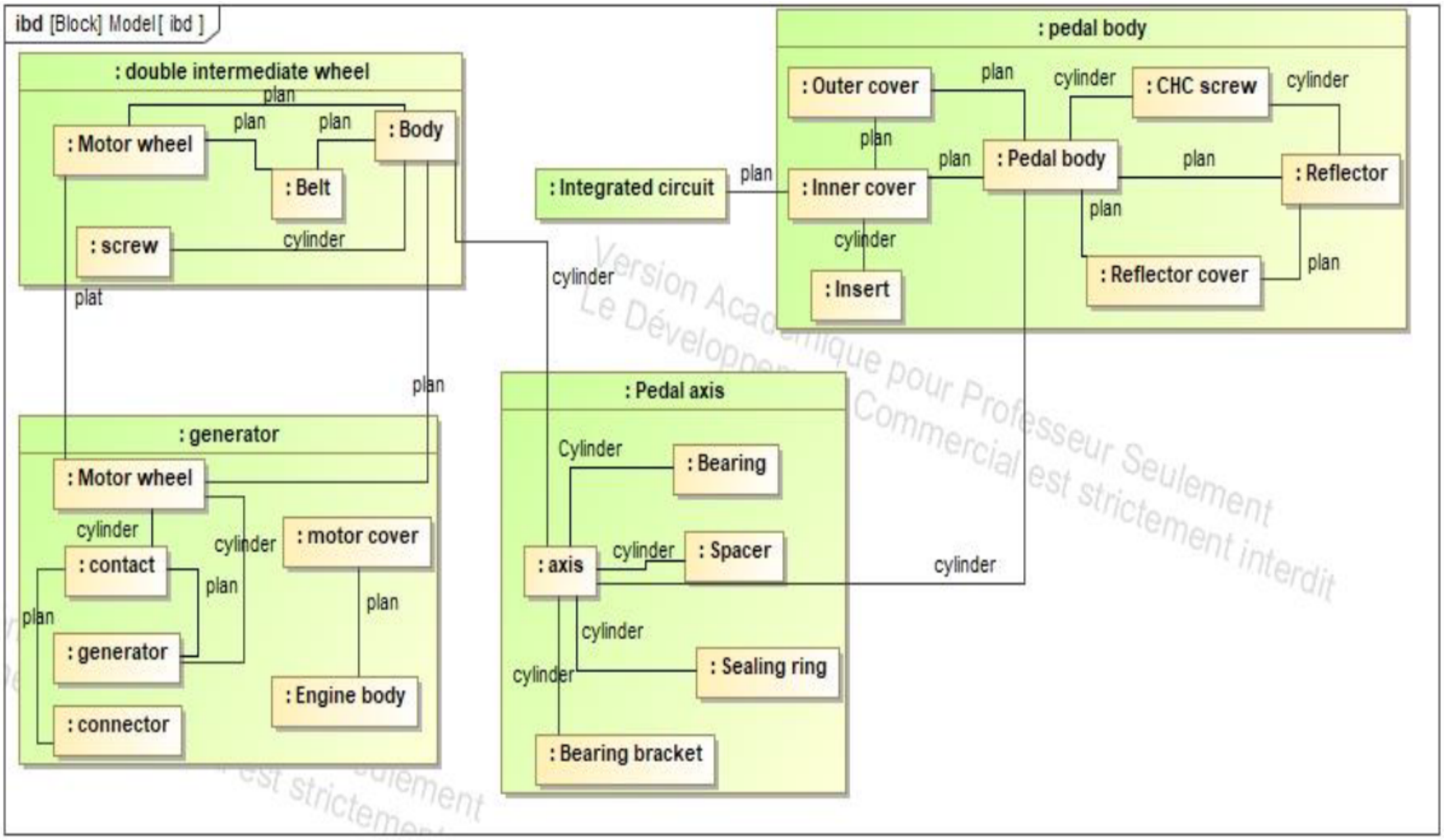

Figure 11

Pedal assembly architecture

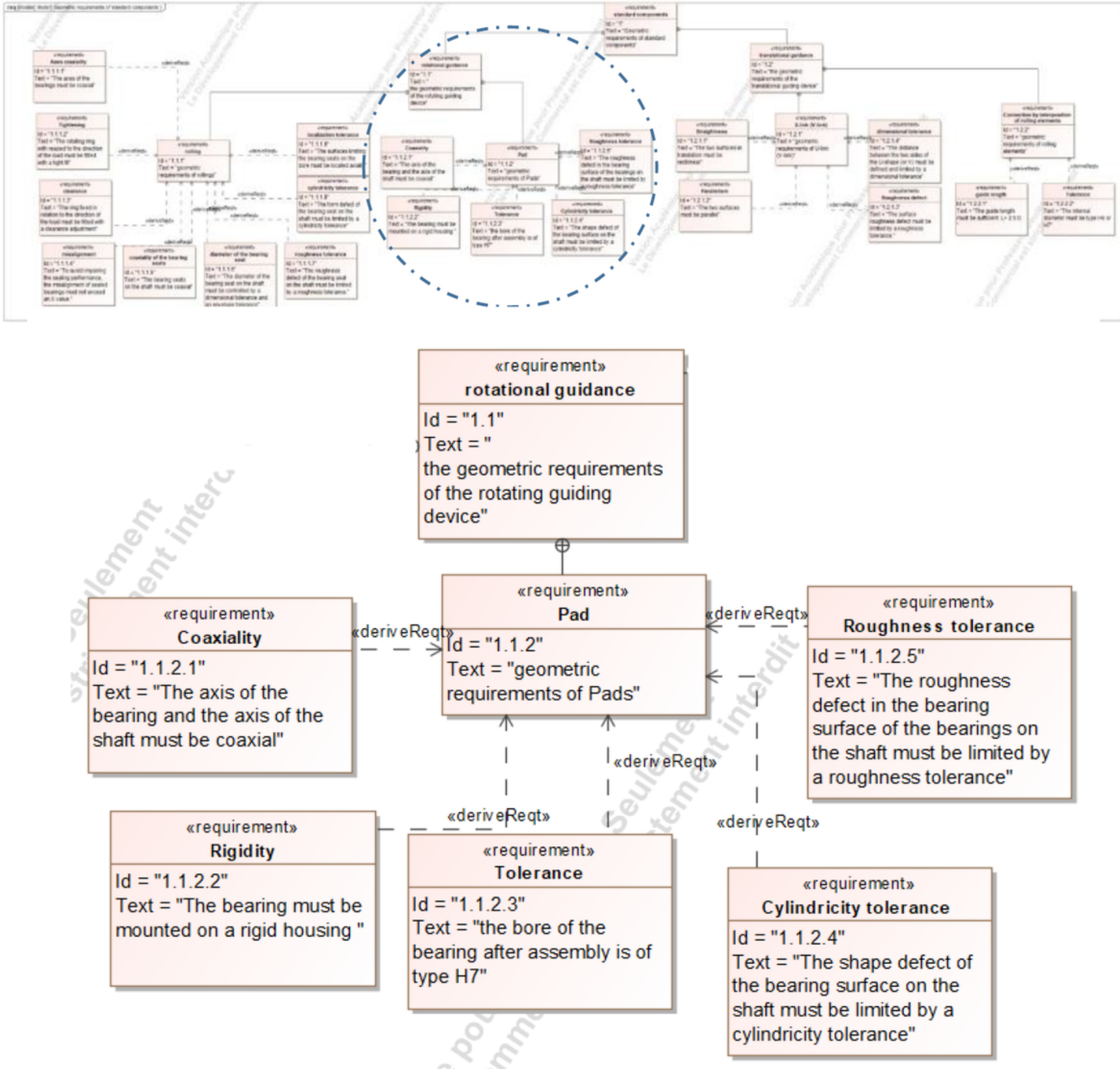

Figure 12

Geometrical requirements of standard components

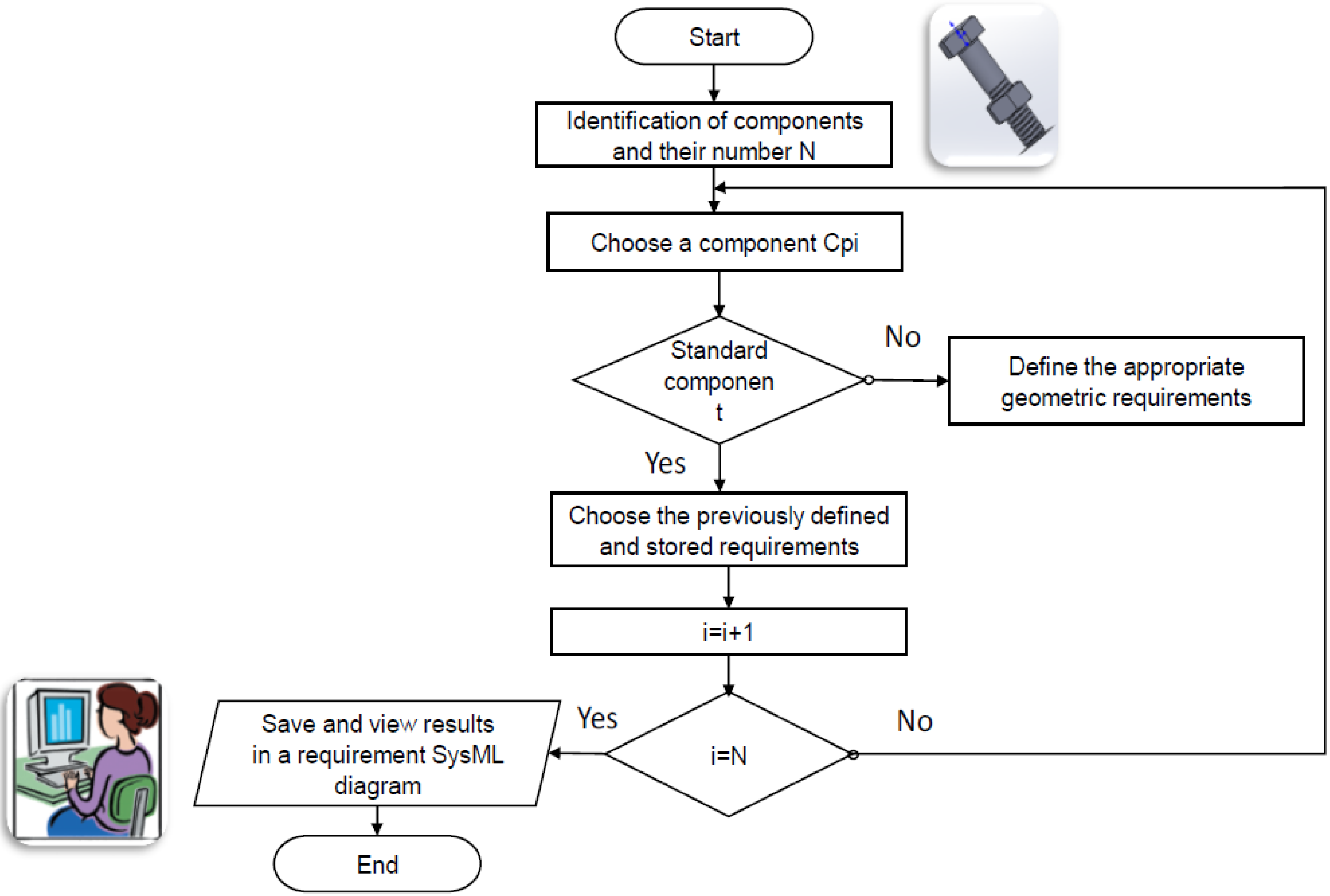

Figure 13

Flowchart of the geometrical requirements specification

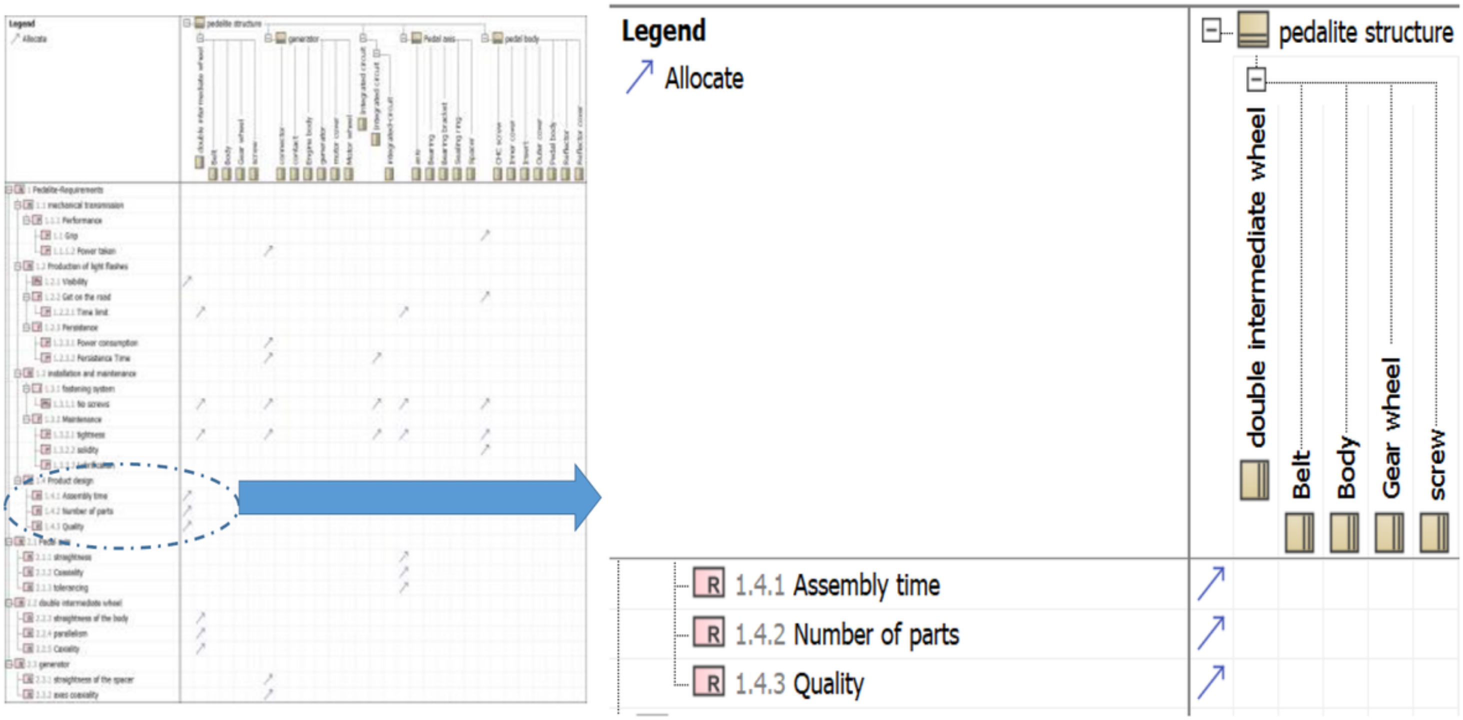

Figure 14

The assembly design analysis indicators validation