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# Interoperability of CAD models and SysML specifications for the automated checking of design requirements

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**Abstract**

Currently and in view of technological development, mechatronic systems have become more and more complex. This will undoubtedly influence the design of products. For this reason, designers do not stop developing new solutions to best ensure customer satisfaction on functional, dimensional and geometrical requirements. However, to achieve a finished product satisfying all stakeholders, designers should face a multitude of problems. Among them, the difficulty of data exchange between the different developers contributing to the design process of a finished product. Several research works have focused on data exchange between Computer Aided Design (CAD) and Computer Aided Engineering applications (CAE) or at the CAD development and manufacturing levels. However, few works study the interoperability between all the product development levels and the system engineering one. For instance, the lack of continuity between the system-engineering model which has a global view on the product, and the CAD model which integrates the parts and assembly CAD data, causes an enormous lost time in the verification and validation process of requirements. In this paper a methodology allowing the interoperability between the system level specifications and the CAD model of a product being designed is proposed. Based on SysML diagrams, the customer needs and the functional analysis of the product lead to the definition of the initial structure of the product assembly. The results of this step are used as an input by the CAD designer to detail the architecture of the mechanical assembly. Finally, the product assembly data required for verification and validation are extracted from the CAD model and then used back to enrich the preliminary SysML model. The system engineer uses the collected data in the SysML model to check and validate the product requirements according to a V model. A pedal of a bicycle was used as an example to illustrate and prove the effectiveness and efficiency of the proposed approach.



*Keywords:* Product Specification Model; SysML; Mechanical Assembly Data; CAD-SysML interoperability

## I. Introduction

The technological development of recent years has resulted in increasingly complex products. Indeed, mechatronic systems are in turn influenced by this complexity and this will undoubtedly influence the work of designers. Faced with this development, the demands of customers keep increasing. For this reason, the goal of designers is to ensure customer satisfaction on all levels.

In order to properly meet the customer's needs, all the requirements must be carefully studied and this requires the interconnection between several disciplines to guarantee it.

The Model Based System Engineering (MBSE), is a multidisciplinary approach that ensures collaboration between the various actors in order to validate the design of systems that present high degree of complexity. One of the languages used by system engineers to satisfy different constraints is the System Modeling Language (SysML) which allows engineers to document the properties from different disciplines to describe the whole solution [1] in an understandable way by all


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actors. Thus, the MBSE approach using SysML is a good choice in system design to better manage all the constraints [2, 3].

In this paper the interoperability concept between the systems engineer step who has a global view on the products to be designed and the CAD step that has a detailed representation of parts and assemblies is developed. This work proposes a new method, which allows the automatic data exchange between system specification models and CAD models which favours the continuity between the two works.

## II. Related works

In system engineering, each product to be designed necessarily goes through development phases that help to satisfy all the requirements sought.

The system engineer details this process in a V-shaped cycle, which illustrates the succession of steps to be validated.

The steps start with a need analysis and end with a validation of the requirements, going through a detailed design step. It is thus important to ensure effective collaboration between system engineers who have a global view of the system and detailed design engineers who have mastery of particular areas such as computer-aided design.

Several research works have focused on the development of both fields of model-based systems engineering (MBSE) and computer aided design (CAD). However, little work has investigated the interconnection between the two engineering fields. Indeed, in the MBSE domain, some researchers were interested in the definition of the functional architecture of each product like proposing new approaches to derive functional architectures from requirements and use cases and to model them in SysML[4].

Other researchers were interested to the validation step such in [5] by using SysML for planning verification and validation on the Large Synoptic Survey Telescope (LSST). Indeed, this approach is used to extend the advantages of MBSE into later stages of the construction project.

There are those who were interested in the inderstanding of mechatronic systems and their architecture. In [6] the researchers have developed a SysML-based methodology for mechatronic systems, which consists of two phases: a black box analysis with an external point of view that provides comprehensive and consistent set requirements, and a white box analysis that progressively leads to the internal architecture and behaviour of the system.

In the CAD domain, researchers have determined whether the estimation of the ease of handling and insertion of parts can be provided by multimodal simulation using virtual environment (VE) technology, rather than using conventional methods based on tables such as the Boothroyd and Dewhurst charts [7].

Some other research works were used to extract CAD data from an assembly CAD model like the Computer Aided LABoratory (CADLAB) tool which constitutes a bridge between CAD system and CAD applications [8].

There are those who were interested in the generation of assembly sequences such in [9, 10] were they proposed an Assembly Plan (AP) generation method based on the simplification of the assembly CAD model. Firstly, the proposed tool allows the simplification of the CAD model by eliminating the connection parts (screw, nut, pin, etc.). After extracting the CAD data from Solidworks© environment, the simplified AP generation can be performed without considering the connection parts. A case-based reasoning module permits the insertion of the previously eliminated parts into the simplified AP to obtain a global AP.

In our research work, we are interested in the exchange of data between the two disciplines given the major importance which lies in the interoperability of these fields which makes it simpler to validate the design step. In fact, much research works have studied the importance of interoperability between these disciplines. For example [8] treated the interoperability process between CAD system and CAE applications helping designers to find the CAD assembly data in complex mechanical assembly model, facilitate the structuring of the useful designing data. In [11] researchers studied the importance of the interoperability between CAD/CAM/CAE systems in order to facilitate the data exchange between all of them.

## III. Proposed methodology

The work of the system engineer and that of the designer are complementary except that a difficulty in exchanging data arises given the difficulty of finding a standard means of communication between them. For this reason, a methodology has been proposed which makes it possible to ensure interoperability between the two fields by favouring consistency and continuity of the verification and validation of the product. This methodology is summarized in the workflow detailed in Fig 1. The workflow is developed to facilitate the exchange of data between the designer and the system engineer who must present a coherent model of the system then check the satisfaction of all the constraints to finally validate the product digital mock-up already designed.

Each step is detailed in the following sections and the proposed methodology is illustrated with a bicycle pedal example, which activates automatically when rotating the crankset. A gear train multiplies the rotation of the central axis, and a generator converts kinetic energy into electrical energy. The latter is sufficient to activate the light emitting diodes of each pedal, and charge a storage capacitor. The residual energy provided by this capacitor allows the diodes to continue flashing for a while even if the rider is stationary.

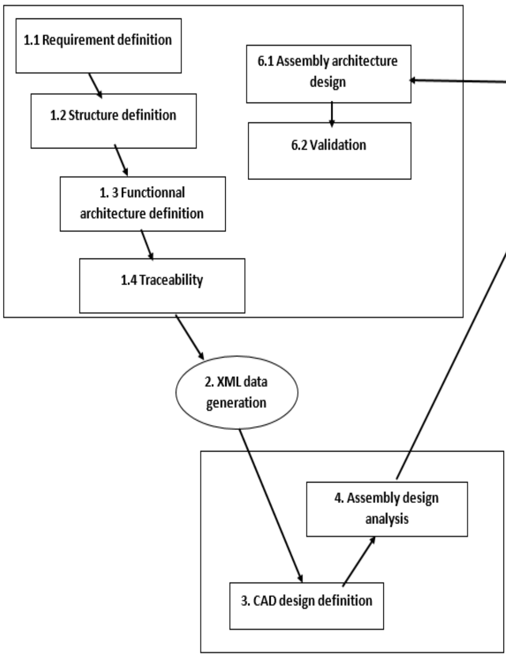


Fig. 1.The workflow of the proposed methodology.

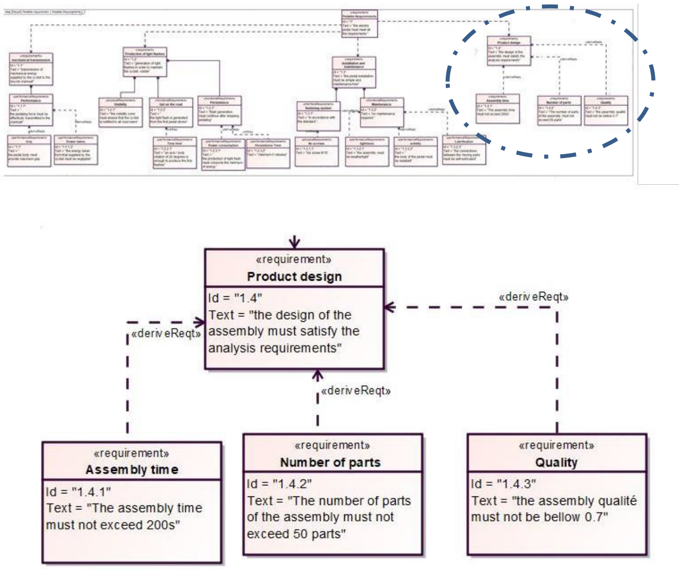


Fig. 2.The requirement diagram of the pedal.

# 1. Global study

## 1.1. Requirements definition

In order to be designed, each product begins with a need specification, therefore an idea that must be well studied and analyzed in order to better understand it. This will involve a multitude of solutions among which the most satisfactory will be chosen.

In system engineering, the definition of requirements plays a central role in the analysis of customer needs. In this activity, the system engineer is called to understand the problem in order to be able to set all requirements that the final product must fulfill. They specify all functions, missions and conditions relating to the implementation of the system.

In this part the system engineer devotes a part to the requirements relating to the analysis of the design solution by imposing maximum values of some assembly analysis indicators (maximum number of parts, time and assembly quality) to verify their satisfaction following the 3D design. These indicators are detailed later in the assembly analysis phase.

The requirements of the system are represented in a Requirement-SysML diagram. Each of them is characterized by its name, an identifier and a text which briefly details its purpose.

These requirements are linked together by links to hierarchically structure all the requirements. In the validation example of our methodology, the functional requirements of bicycle pedal system and a zoom in the design part are represented in Fig. 2.

## 1.2. Structure definition

After delineating and taking into account the functional requirements, the system engineer is invited to fix the initial structure of the assembly.

A mechanical assembly is a set of parts and/or subassemblies linked together by assembly constraints. To design it, all the details of each component must be taken into account. Since the system engineer is not required to be a specialist in CAD design considering that he has a global view of the mechanism. For this reason, he is invited to model the overall structure of the assembly, which contains only the blocks that they deem essential in the functioning of the system.

Using system-engineering tools, this primary structure can be illustrated in a SysML block diagram. It will contain the fundamental block of the assembly related to other sub-blocks that constitute it, connected by composition links, all without going into the details of each block.

In the illustrative example, the pedal must be made up of 4 essential subassemblies which are: the axis of the pedal, the body of the pedal, a generator and a double intermediary wheel as shown in Fig. 3.

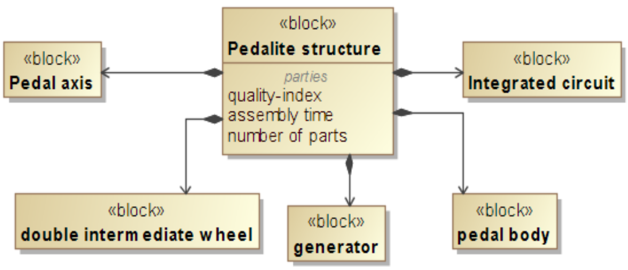


Fig. 3.The initial structure of the pedal.

### *1.3. Functional architecture definition*

At this stage the functional requirements as well as the initial structure of the assembly have been modeled in the MBSE environment. To have a detailed view of the assembly and its functions, it is necessary to analyze it as well as possible before starting the 3D design phase. For this reason, the activity of defining the functional architecture turns out to be an interesting step in understanding the mechanism.

This step consists of determining the set of functions that the system must perform. It specifies the functional needs of users. This specification facilitates the comprehensibility of the process to be followed to facilitate the definition of the sequence of functions to be satisfied by the product.

This functional architecture is modeled in a SysML activity diagram. It is used to model the operating steps. Each function has an input which allows its activation and its output is an input for the function which follows it.

In the example of the pedal, the functions that it must satisfy are represented in Fig. 4. First, the mechanical pedaling energy must be transmitted in order to adapt it later. The next step consists in converting this mechanical energy into electrical energy which must be well managed in order to produce light flashes.

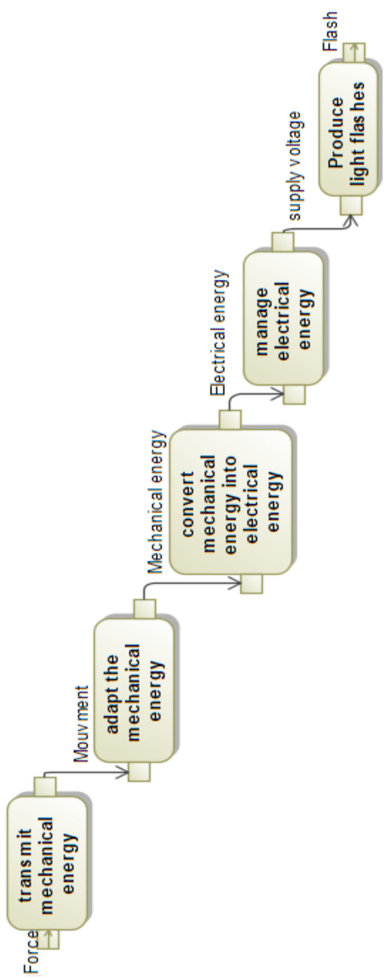


Fig. 4.The functional architecture of the pedal.

### *1.4. Traceability and allocations step*

The traceability step has a major importance in improving the quality of the assembly. Indeed, through this step, the system engineer allocates each block of the assembly structure to the requirement it must meet. The modifications that will be executed on any of the requirements will automatically influence the assembly blocks. Thus the link between the requirements and the components of the assembly 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 requirements that have been imposed.

In the example of the pedal, this can be represented in a requirement diagram where each requirement is associated with the subassembly that it must satisfy by linking them with links of satisfaction.

## 2. XML-MBSE data generation

Once all the informations related to the understanding of the system, from a functional and technical point of view has been detailed, the extraction and automatic generation of this information become a very important step to allow their transmission to the designer in order to design a satisfactory mechanical assembly on all levels.

The purpose of this step is to transmit a file understandable by designers which summarizes the work previously detailed by the system engineer. For this reason, a simple, easy, accessible and understandable format by everyone can be chosen. The extraction format is Extensible Markup Language (XML), which has now become a universal data description format. It offers interesting opportunities to allow the development of new integration strategies within information systems. So, new macros were programmed in python are used to facilitate the exchange of data between the two fields in order to better improve the collaborative work. Using these macros, it becomes possible to store data collected from the MBSE environment and to extract them in XML format, which will be used later by the designer to fully understand the work previously detailed without having to resort to complicated means. The resulting file is a well-structured file that models in a simple way the work of the system engineer.

Fig. 5 illustrates the xml file resulting from the pedal example. The first part is dedicated to the requirements to be satisfied by the pedal, the second illustrates its initial structure and the third contains its functional architecture.

```xml
<?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-consum
          <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 0.8</Quality>
      </Product-design>
    </pedalite-requirements>
</Pedalite>
```


Fig. 5.The XML-MBSE data extraction of the pedal

## 3. CAD design step

In order to be close to the perfect result that we are aiming for, the CAD specialist will carry out the work of the system engineer. During this step and with the help of digital simulation techniques and computer tools, the designer is led to study the informations collected from the system engineering and generates the digital mock-up of the product. This modeling will allow a much more detailed representation of the mechanical assembly and to all the details of parts that constitute it.

Once the designer has completed this activity, the assembly design is then ready to be submitted for analysis. The 3D CAD design of the pedal is given in Fig. 6.

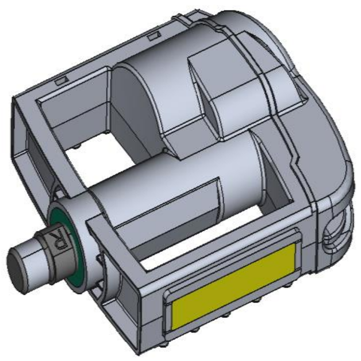

Fig. 6.The CAD design of the pedal.

## 4. Assembly analysis step

A good design solution should be well designed, but also it has to meet all the requirements. For this reason, each designed solution need to be analyzed by studying its response to the assembly analysis metrics previously proposed by the system engineer. These metrics are: T, N and E where:

T: total assembly time: this is an indicator that gives the value of the time required for the assembly to be properly assembled and finished.

**N**: minimum number of parts: this is an indicator that studies the number of parts that must be required after the design, since there will probably be parts that will not influence the functioning of the mechanism so can be eliminated.

E: assembly quality which is an indicator that is used to control the quality of an assembly and which is proportional to the time and number of parts in the assembly.

These metrics are calculated and generated automatically after finishing the design. They present a major importance in verifying the response of the design to the requirements imposed by the systems engineer.

## 5. XML-CAD data generation step

Once the assembly analysis step is done and the design solution is validated according the set of identified metrics, the XML-CAD data generation step can begins. At this stage, it is necessary to have a mean that allows the transfer of the collected data from CAD environment to the system engineer to have a detailed vision on the detailed design of the assembly so that he can continue his work. In this context, the XML format is chosen because of its ease of understanding. The CAD data extraction process is automatic, through macros that we developed in order to generate informations related to mechanical parts constituting the assembly, and converts all the necessary informations for the validation of the assembly by the system engineer. These data are related to the assembly and its related components such as the name, volume, area, assembly time, geometric constraints between the parts in contact, etc.

The XML file resulting from the generation of the CAD data of the pedal is sent to the system engineer in order to validate the design solution.

## 6. Enrichment and validation

### *6.1. Definition of the assembly architecture*

In this step, the system engineer is invited to add enrichments to the structure of assembly initially proposed. This new structure will make it possible to model the assembly architecture by adding links between parts, based on informations collected from the CAD-XML file.

The architecture of the pedal assembly is represented in an internal block diagram.This diagram contains the parts making up the assembly with the links between them.

### *6.2. Design validation step*

This is the step that sums up the interconnection between MBSE and CAD models. All types of mechanical systems can be validated using the following method: Using allocation matrices from SysML, the system engineer gathers both data. The ones collected from CAD, which are mechanical parts, and the others collected from MBSE, which are requirements. During this step, he models all the requirements in the rows of the allocation matrix and tests them one by one. Therefore, if the selected component satisfies the attributed requirement, he confirms its satisfaction by manually adding “satisfy” relation in the appropriate box, which combines the requirement and the mechanical component. Then, he goes on to test the next one. Otherwise, he returns a report to the designer in order to make the necessary appropriate modifications in the designed solution.

Fig. 7 presents the validation of the pedal assembly solution. For example, one of the requirements that the system engineer needs to check is that related to the analysis indicators requirement, which are E, N and T. He checks if the assembly satisfies all the requirements or not. These indicators can help him to decide whether the proposed solution is the most satisfactory by comparing the values proposed by the system engineer with that calculated through the designed solution. In the treated example all of them were satisfied so the solution can be retained.

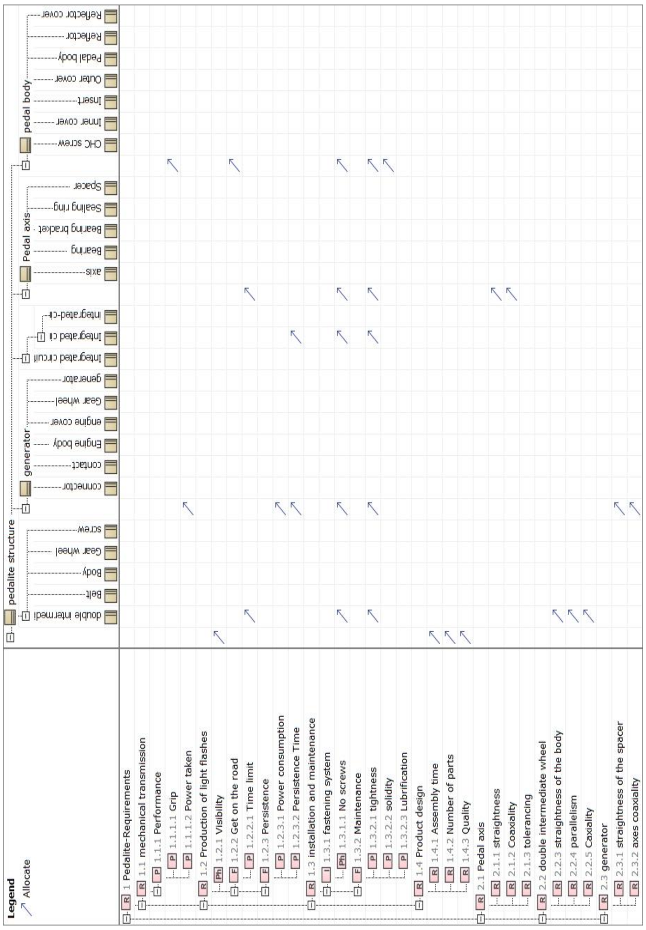


Fig. 7.The validation of the pedal design.

## IV. Conclusion and future works

Given the low presence of means that facilitate the automated exchange of data between MBSE and CAD models, we proposed in this paper a methodology allowing the continuity of product develomemnt between the design specification level and the detailed design level.

The first deals with the product in the MBSE environment to collect all the requirements that the designer must take into account in phase two, which is the CAD development. The main goal of the proposed methodology is to facilitate the data exchange so as not to lose information and to allow the system engineer to make decisions, according to the requirements imposed, to validate or not the design solution proposed by the designer.

Based on this cooperative work between the two disciplines and after the validation of the design solution, it will also be necessary to develop this work to allow the designers to automatically generate the assembly and disassembly sequences of each product. That obviously makes the goal of work in progress and future work.

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