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Systems engineering analysis approach based on interoperability for Reconfigurable Manufacturing Systems

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Abstract

In this paper, we propose a systems engineering approach for the analysis of reconfigurable manufacturing systems. This work contributes in the implementation of the systems engineering perception in industry 4.0 researches framework. The approach is based on interoperability concept in order to correlate diverse requirements as input for the analysis, and generate a result based on reconfigurability parameters. Beside the approach itself, this paper presents an application on a reconfigurable machine tool that demonstrates the applicability of the developed method.

Keywords— Industry 4.0; interoperability; reconfigurability; manufacturing systems; systems engineering;

I. INTRODUCTION

The manufacturing predispositions reflect some fluctuations on the customer demands over the years, related to constantly changing product volumes and varieties. This requires developing new manufacturing systems, switching from mass production and conventional mass customization to agile customization, with a higher reconfigurability level, in less time and lower production costs [1].

Traditionally, the majority of heavy constraints related to unpredictable changes, making manufacturing systems highly complex, are not taken into consideration in the design of Dedicated Manufacturing Systems (DMSs). Indeed, DMSs have been designed to produce specific simple repetitive products. These traditional manufacturing systems are efficient when the production volumes are high and the product is manufactured over an extended period of time [2].

Contrariwise, Flexible Manufacturing Systems (FMSs) are designed to manufacture a large variety of products. These systems are economical when the production volumes are low and large varieties of parts are produced.

However, rapidly changing market requirements have made traditional DMSs and conventional FMSs unable to meet the new market needs [3, 4]. Hence, Reconfigurable Manufacturing Systems (RMSs), are revolutionizing the way industry is functioning [5], and consequently, has been considered as one of the most important axes that contributed in the launch of industry 4.0 concept. Nevertheless, the analysis of the RMSs' reconfigurability during the design phase is a challenging task.

In this paper, we propose an approach for the analysis of reconfigurable manufacturing systems, by facilitating the interoperability between systems engineering modeling environment and 3D CAD modeling tool. The functional and non-functional RMS design requirements are modeled using SysML language and the geometrical specifications of RMS modules are defined in a 3D CAD modeling tool. The reconfigurability analysis is performed in an integrated way using developed reconfigurability analysis metrics.

This paper is organized as follows: in section 2, a literature review is given about researches and studies related to Industry 4.0, reconfigurable manufacturing systems and systems engineering. Our approach for reconfigurability analysis of RMSs is described in Section 3. Section 4 presents an application of the approach to a reconfigurable machine tool. Finally the paper is concluded in section 5.

II. STATE OF THE ART

Nowadays, industry 4.0 is a scientific theme of debate where every sector of research would like to take a part of its development. First, Industry 4.0 is a strategic initiative of the German government that was adopted as part of the "High-Tech Strategy 2020 Action Plan" in 2011. Indeed, a major discussion on Industry 4.0 has started in Germany, which has also spread at the same time to other countries, like the US and Korea. The idea behind this term is that, the first three industrial revolutions

came about as a result of mechanization, electricity and IT [7]. Industry 4.0 environment was chosen to meet the needs of future production systems with a high level of adaptability. To accomplish this challenge, many researchers proposed to integrate Cyber Physical Systems (CPSs) into the production sites in order to create 'smart factories'[8].

Authors in [9] presented the 5C architecture for Cyber-Physical Systems in Industry 4.0 manufacturing systems, which is providing a viable and practical guideline for manufacturing industry to implement CPS for better product quality and system reliability with more intelligent and resilient manufacturing equipment. From another side, S. Weyer et al. [7] gave an overview of the current status of the Smart-Factory-KL initiative to build a highly modular, multi-vendor production line based on common concepts and standardization activities. J. Schlechtendahl et al. [10] presented also their approach, which is based on a communication gateway and an information server for existing manufacturing systems to be expanded to I4.0 concept, in order to reach a high level of manufacturing systems reconfigurability.

A. M. Farid [11] has defined the term reconfigurability as "the ability to add, remove and/or rearrange in a timely and cost-effective manner the components and functions of a system, which can result in a desired set of alternate configurations". The definition recommends the idea that a manufacturing system with high reconfigurability should require less time and effort in order to reconfigure the system. W. Covanich et al. [11] have studied the measurement of the ease of reconfiguration and proposed Design Structure Matrix (DSM) as a solution based on capturing the different types of interaction between modules. Similarly, D. M. Tilbury and S. Kota [12] have described an approach for integrating machine and control design for reconfigurable machine tool. The authors used some metrics such as work envelope, the number of degrees of freedom, the number of modules, and the dynamic stiffness to evaluate the reconfigurability. Moreover, R. Riba et al. [1] have defined two mathematical equations for reconfigurability analysis: Machine's reconfigurability rate (R_{mt}) and Cutting Tool's reconfigurability rate (R_{ct}), as two metrics containing different parameters related to geometric, functional and non-functional requirements. Furthermore, R. Katz [13] has addressed the impact of the machine tools reconfigurability on measured geometric features such as flatness, parallelism and profile.

Several researchers have studied RMSs and RMTs as systems of many interconnected parts. Consequently, they can be considered as complex systems according to E. Bonjour et al. [14]. To manage the design process of such complex systems, Systems Engineering (SE) is today positioned as the adequate discipline. Indeed, systems engineering is an "interdisciplinary approach and means to enable the realization of successful systems" [15], which focuses on the entire system rather than on different components independently. Many standards dealing with SE arose to describe the processes and activities to be carried out to assist the engineering of complex systems such as the IEEE 1220 standard, which focused on requirements, functional analysis and allocation. Besides, there is The EIA 632 standard as well as the well-known standard ISO-IEC-15288,

that describes the processes of the whole lifecycle of a product [16].

Therefore, systems engineering approaches can help designers in developing RMSs which can satisfy Industry 4.0 needs, in terms of reconfigurability and modularity.

The authors in [5, 13] consider the modularity as the compartmentalization of the whole system or machine into subsystems or parts and making the system by combination of some separable subsystems or parts to change the structure in order to make different functionalities [3].

They also consider reconfigurability as a concept more than modularity. It means for instance, a reconfigurable system is a modular system that has some other characteristics that can be summarized as [3, 5, 13]:

Scalability: is the ability to change the production capacity by reconfiguring the structure of the manufacturing system. This characteristic of the manufacturing system is for increasing its productivity when there is unpredictable change in the quantity of demand.

Integrability: is to integrate modules rapidly and accurately. This is possible by sets of mechanical, informational and control interfaces to fit the modules together properly. The speed of the replacement of the modules is very important because if set-up time or ramp-up time becomes long, the productivity will be low and the reconfigurable manufacturing system will not be cost-effective.

Convertibility: is the ability of the manufacturing system to change the functionality by changing its structure. It helps us to produce the new variants of products with the existence manufacturing system.

Customization: is a kind of limited and needed flexibility for the specific defined family part of the manufacturing system. Family part includes the parts that have similar specification, that we need the least change in the manufacturing system to produce these parts in the family just by a rapid set-up time. To produce another part family group we need a longer time to change the manufacturing system called ramp-up time.

Diagnosability: is the ability to read the current situation, find the root cause of defects automatically, and rapidly correct the error. This characteristic is very important because RMS is a kind of multifunctional system that if it breaks down, the whole of the manufacturing system will face big problem and the production line will stop. The above principles of RMS make the production cost-effective and rapid. It means that RMS is a kind of manufacturing system with needed flexibility and acceptable productivity.

The integration of all the requirements related to the previously cited concepts necessitates a solution to combine them. In this work, we propose a solution based on interoperability to face this challenge.

The complexity of decomposing a system into modular parts and then integrate them to make a reconfigurable system with different functionalities, requires a systems engineering methodology and tools to manage the requirements, the functionalities, the module's structures and their dependability. However, not all the data and models developed during the design process of the reconfigurable system can be handled with

a unique modeling tool. Therefore, interoperability is considered as an important solution in such cases of modeling and analysis of complex systems.

Interoperability allows different information systems to communicate, execute instructions, share data, or otherwise, to make interaction between fundamental requirements in a networked environment [6]. Interoperability was suggested in several previous research works for the modeling and the analysis of complex systems. For instance, interoperability was used in [17] for the analysis of mechatronic and multi-physics systems. Reconfigurable manufacturing systems can therefore be considered as mechatronic systems, since they integrate in a synergistic way mechanics, electronics, automation and software codes. Like mechatronic systems, reconfigurable manufacturing systems requires multi-criteria indicators for their analysis [18]. Depending on the level of detail, different models can therefore be developed for the reconfigurable manufacturing systems. Interoperability between multi-level models can be managed with multi-agent solutions [19].

In our study, we suggest to interoperate two modeling environments with two different level of abstraction. A SysML-based environment to handle a big quantity of information related to requirements, functionalities and architectures of the reconfigurable system. The second environment is a 3D modeling environment to manage the geometrical specifications and topological links between reconfigurable systems.

In next section, we present our approach for integrating the information necessary for the analysis of reconfigurable manufacturing systems.

III. APPROACH DESCRIPTION

This section describes the approach for reconfigurability analysis based on the interoperability concept and explains its different phases. This will help manufacturers, thanks to systems engineering facilities, to make manufacturing systems more flexible to be manipulated and more adaptable to alterations.

The process of modeling in our approach is established according to systems engineering fundamentals, in order to be generalized, so that its implementations could cover several application cases.

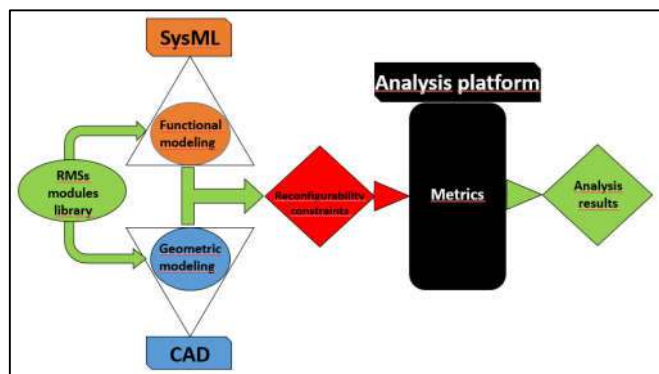


Fig. 1. Reconfigurability analysis approach of RMS based on interoperability

Figure 1 describes our approach for the reconfigurability analysis of manufacturing systems. The input in this method are the predefined models of RMSs modules' configurations. It means that manufacturing system elements have to be firstly modularized. Then, each module is specified with two types of requirements: functional and geometric. On the first hand, functional requirements are defined using SysML language. Indeed, several systems engineering methodologies was previously developed based on SysML Language [16], and SysML is being widely used for various purposes such as emphasizing the inter-modular adaptability requirements, in which we are interested in this paper. Subsequently, SysML helps designers in specifying the compatibility's criteria between different modules. On the other hand, the geometric requirements are defined using 3D geometric modeling tools in order to specify the parameters that are useful in analyzing the RMSs' reconfigurability.

In the second stage, all requirements are imported and transformed into a unique format, as to facilitate their management. Most often, the main problem is strongly related to interoperability between used modeling/programming tools and their ability to intercommunicate even with standardization. Thorough researches will be dedicated for this issue, to put all requirements in one informational communication environment. When all requirements turn into coherent information, a sort and selection operation will be executed referring to metric's requirements for the reconfigurability analysis platform. The core of the approach, called black box in figure 1, includes thresholds, ranges, algorithms and mathematical equations. Similarly, this black box is connected to the same space of communication as the requirements, as to ensure the ease of the information treatment. Finally, results defined as output of the platform, according to the primitives (Basic modules). Some useful complex solutions could therefore be generated, based on the possible interactions between primitives. These solutions are the appropriate configurations satisfying the highest rate of reconfigurability.

The approach described here allows two kinds of stakeholders to integrate their information within the same platform. Firstly, the downstream developers, such as system's engineers working in top-down method to generate functional concepts from requirements. Secondly, the upstream specialists, such as manufacturing engineers and finite element method (FEM) specialists, working in a bottom-up method, to generate specific information and knowledge about manufacturing and system performance. Downstream developers need the information and knowledge coming from upstream specialists to help them in making decisions about the reconfigurable system architectures to keep during their development process. The manufacturing and FEM specialists also need the information developed during the downstream process as inputs to develop physical solutions matching the functional requirements. Therefore, the platform allows systems engineers and multi-domain specialists to share and exchange information and knowledge, and then cooperate to develop the reconfigurable manufacturing systems.

IV. APPLICATION OF THE APPROACH TO A RECONFIGURABLE MACHINE TOOL

Reconfigurable machine tools (RMTs) are an interesting example of reconfigurable manufacturing systems (RMSs). The RMTs are the development of the Computer Numerical Control (CNC) machine tools by taking into consideration other constraints such as a specific range of production requirements and cost-effective production. Figure 2 shows examples of RMTs.

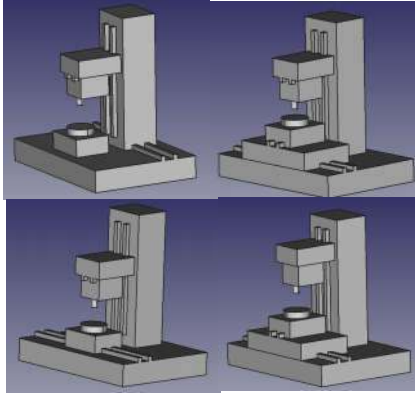


Fig. 2. Examples of RMTs

The 3D design of every configuration is created by combining the modules developed using FreeCad software. The attributes of the modules and configurations, such as working space, are used later for the reconfigurability analysis, by integration the 3D information with the requirements and functional attributes.

The RMTs comprise the same characteristics of RMSs but with more specification requirements at the operational level. So that, in systems engineering point of view, RMS, could be considered as a generalization of RMT. Therefore, RMTs, as well as RMSs, are essential parts for the development of the Industry 4.0.

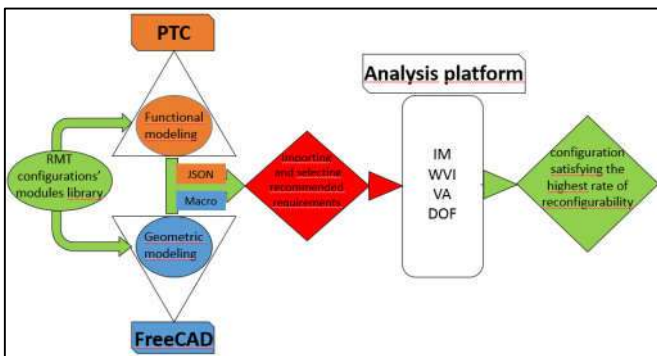


Fig. 3. Implementation of the reconfigurability analysis approach for RMT

The RMT's approach is coincident with the generalized concept's architecture. However, it is so concrete in using tools

for each step of the proceeding. Figure 3 shows the implementation of our approach in the case of RMTs. FreeCAD and SysML/PTC Integrity modeler are the modeling tools for the collection of requirements. The white box in figure 3 is the analysis platform developed with Python language. This choice is justified by the fact that FreeCAD is built in Python scripts and both of them are open sources, simple in use and free cost. Therefore, it is needed to develop special scripts and integrate them in FreeCAD as macros (figure 4), in order to import geometric requirements from FreeCAD to Python. These macros was added to FreeCAD functionalities to be used for launching FreeCAD interface, opening the target part, and generating its parameters. Moreover, with an intermediate database compatible with PTC Integrity modeler, called JSON, functional requirements could be imported and stored in JSON format. Obviously, with a simple Python script, all requirements are ready to be operated.

After the integration of all data in a unified communication environment, which is Python software, the next step is about sorting and selecting the parameters requested in the white box. The latter bases its analysis operations on the following metrics:

- IM: Interaction Matrix specifying the adaptability between modules' configurations and generates from its algorithm, the validate configurations of machine tools.

- WVI: Work Volume Index defined with the following formulae:

$$WVI = \prod_{i=1}^n \frac{Ri \text{ of Design}}{Ri \text{ of Requirement}} \quad (1)$$

R_i: range of movement

WVI is determined from three geometric parameters; useful surface for manufacturing and its height as well as the total volume of the module. Moreover, WVI should be between 1 and 1.5. If it is less than 1 it is not acceptable because it does not cover the whole of the machining space and if it is more than 1.5 the machine tool is over designed and we should pay unnecessary cost [20].

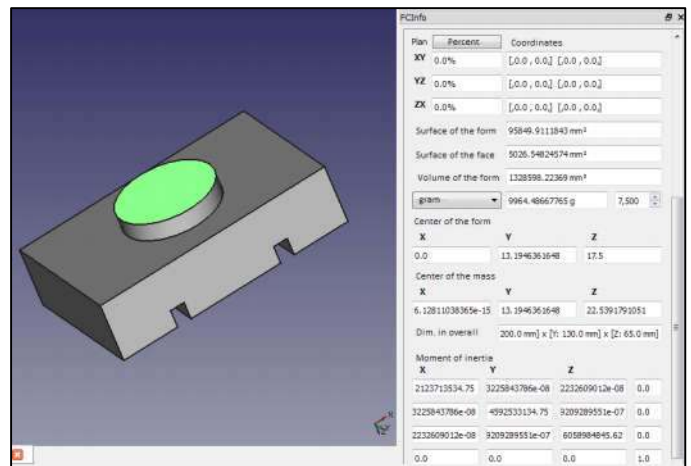


Fig. 4. FreeCAD interface with FCInfo macro for geometric requirements

- VA: vibration analysis, also called dynamic stiffness. It is one of the important characteristics that have to be verified after the

configuration choice. To prevent chatter and have better quality of the machined product, vibration control of the modules is obligatory. Some tests on the configurations could be done by some sophisticated dynamic simulation software like ANSYS, LMS and others.

- DOF: Degree Of Freedom that should be as low as possible because each DOF causes more instability and needs its own control that means an extra cost without benefit. IM and DOF are results of functional requirements that are imported from PTC integrity modeler bridged by JSON. Although, the two others are considered as geometric metrics gathering their parameters from FreeCAD macro. The figure 5 shows the platform developed in Python language for the reconfigurability analysis.

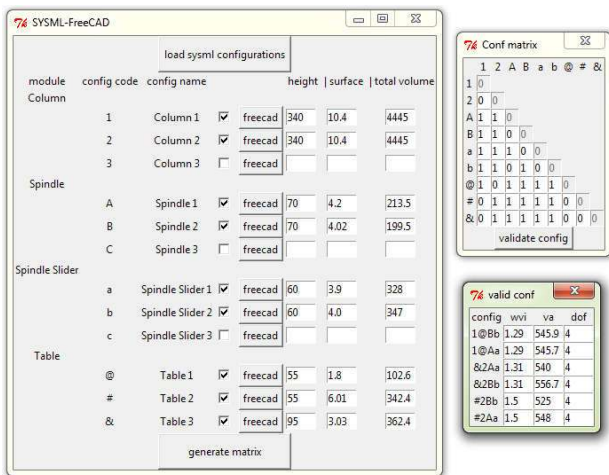


Fig. 5. RMT reconfigurability analysis interfaces

A. Platform description

Our platform for the reconfigurability analysis is composed of three interfaces as follows. The main interface shows functional and geometric requirements. Indeed, the user chooses the configurations modules and then, generates the second interface named “conf matrix”. The latter presents the interaction matrix that have to be completed with ones and zeros. The number one (1) means that the interaction between module configurations is possible. But, the zero (0) or empty text field means the opposite. The validation of the interaction matrix leads to the selection of the possible RMTs’ configurations, generated from modules combination. These configurations are shown in the third interface, with their three criteria that helps the user to find the best RMT.

B. Interpretation and results

Our method supposes that the system’s engineer chooses the best RMT(s) according to the integration of the expertise based on thresholds and rates coming from the different stakeholders. The vibration analysis is executed outside the platform, by using ANSYS software; and the results are integrated manually in the developed platform. The figure 6 shows a vibration analysis execution for one of the selected configurations.

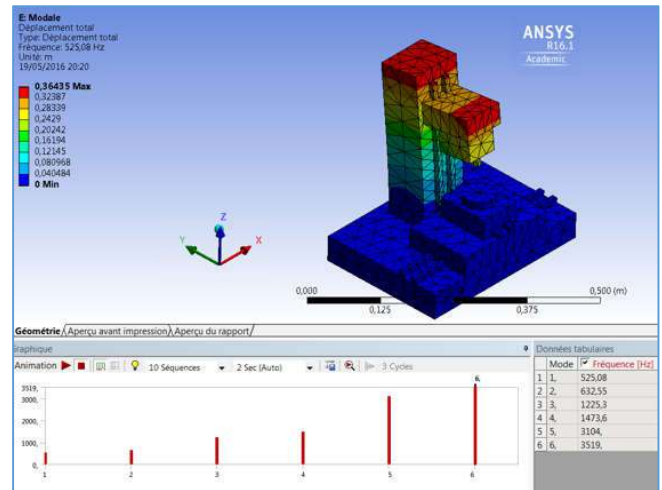


Fig. 6. RMT vibration analysis

The results found in figure 5 for the six configurations and shown in the third interface, which is called “valid conf”, could distinguish each configurations so that the user could easily select the best configuration.

V. CONCLUSION

This article has presented a systems engineering approach for the reconfigurability analysis of RMSs. The developed concept provides an aid in the identification of the appropriate configurations based on interoperability concept creating a homogenous communication environment between different languages. The platform allows engineers working in downstream process to collaborate with specialists working in upstream process, to share and exchange knowledge, and therefore to help them in taking the good decisions to choose the best reconfigurable manufacturing system architectures.

An application of the approach was made on RMTs. This approach simplifies the research of the suitable configuration for the manufacturing system as well as the made-to-order product in an efficient and rapid way.

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