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Towards a reference model for configuration of reconfigurable manufacturing system (RMS)

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Abstract. Reconfigurable Manufacturing Systems (RMSs) offer the ability to change organizations to fit changing contexts. Modularity, both physical and logical, is an essential feature of RMS. Not only because it allows a wide variety of use of the system, but also because it allows to determine the other characteristics of RMS. We propose in this article a new way of defining a configuration for RMS, based on modularity. The module-based view includes four aspects: physical, control, performance and simulation, taken at different levels: system, machines or component. The introduction of the virtual view of the module aim to align the proposition with the requirement of industry 4.0 (The RAMI 4.0 architecture). Simulation and performance concern the technical, ecological or even economical aspect of the system. The module-based view of the system allows a decomposition, a description and an accurate analysis of the system, that leads to a better knowledge of the system, its components and allows a better approach to the reconfiguration process: an industrial case study is presented for illustration. A reference data model emerged from module-based view of the system. The purpose of this reference model is to create a configuration database that can be used as input to a reconfiguration decision process

Keywords: modularity, module-based configuration, reference model, reconfiguration process, industry 4.0.

1 Introduction

Within the context of Industry 4.0, production systems have to adapt to different context changes. Reconfigurable Manufacturing Systems (RMSs) are designed to fit these challenges. Reconfiguration consists in the transition from one *configuration* to another at a given time to match with the needs that arise. This requires an in-depth knowledge of the system, and a clear definition of the concept of configuration. The more complex the system, the more the difficult it is to cover this task, due to the many parameters: the physical aspect of the system has to be considered, as well as the logical aspect [1] and performances (due date, cost, environmental criteria, etc). One of the most common techniques used to support complex system analysis is simulation, as it faithfully repli-

cates situations as close to reality as possible [2]. Yet, one drawback remains, the definition and description of RMS *configuration*. Many research exists in this area and each one gives a particular consideration to the *configuration*. [3] and [4] consider configuration as the result of the process of determining which machines should be added or removed in case of sudden changes. They address a layout-based method to choose the suitable configuration for a system. According to this perspective, the configuration of a system is the layout of the machines in this system (the physical structure). Other research take into account the logical aspect [5], [6], whereas [7] use KPIs such as production and quality rate to identify and define a configuration. [8] argue that the energy consumption or the cost of implementation and maintenance of the system have also to be taken into account. These different considerations are useful in the configuration description as they give decisional information about the system. However, they need to be consider simultaneously, i.e the configuration definition and description should formally involve the previous mentioned (physical, logical, performances, etc.). As far as we know, research undertaken in reconfiguration area has been more focused on technologies of design and decision-making tools. Up to now, very few research has proposed formal definition, including both physical, logical and related KPIs description, that could support the decision-making. The focus was to propose informational model to formally represent the configuration. An ontology- based model proposed by [9], a model for control logic by [10] and an informational model provides by [11] are some example. Still, a formal definition and description are lack.

This paper aims to address this issue, by proposing a new way to formally define and describe a configuration for RMS, based on modularity. The proposed definition involves physical and logical aspects, as well as KPIs, and virtual aspects. In digital manufacturing simulation is widely used to evaluate configuration alternatives. We believe that for reconfiguration decision process it is important to relate this virtual aspect to the real world situation through simulation, as it offers god alternatives of previewing and evaluation [2]. Moreover, it allows our proposition to get align with the RAMI4.0 architecture [12], especially the second layer (the need to have a transition between real to digital world). The simulation model could include both shop floor simulation, ecological impact simulation and also economical simulation- as far as these three dimension are essential in reconfiguration decision process [8]. The remainder of the paper is as follows: a module-based view of configuration is introduced and used within a case study. This module-based view leads to a reference model used to formalize the description and characterization of configuration. The main purpose of the reference model is to achieve to a database of configurations, that will be used in the process of reconfiguration decision-making.

2 The module-based view of configuration

2.1 Modularity as a basic requirement for RMS

Modularity both physical and logical enables large variety in utilization of the system. It is essential for reconfigurability and constitutes a basic requirement for RMS, that leads to the determination of the other RMS characteristics. Indeed, elements can be put together either to adjust the production volume (scalability), or to add functionality

to the system (convertibility), or to produce more customized products (customization). Moreover, the part-to-part analysis of the system ensures the discovery of the real causes of potential problems (diagnosticability), and of the possible solution to implement (reconfiguration strategy). Additionally, putting modules together involves either common interfaces between these modules, or intermediary element to join it. In the first case, modules are considered integrable, because they share common interfaces (integrability).

2.2 A module-based view of configuration of RMS

[13] describes configuration as a set of resources connected together with a control logic. We propose to see configuration as an aggregation of modules (physical, control, simulation and KPIs) taken on different levels. According to the precision degree wanted for the description, the level could refer to the system level, machine level, component level or even sub component level description. The module-based view of the configuration shows that system components are fractal- each module is made of another module, and both has the four mentioned aspects (physical, control, KPIs, and simulation). (**Fig. 1**)

The physical module (PM). The physical module represents the resources of the system. It can refer to workstation, operators, transportation system, storage system, etc. Each PM is managed by a control module. The use of a configuration leads to some KPIs related to the PM. Moreover, when the PM cannot be implemented, the associate simulation module can be used to evaluate those KPIs.

The control module (CM). It is the location of the system's intelligence and decision-making. Here, decisions are made to satisfy production goals under constraints. The control module is in charge of the management of the physical module.

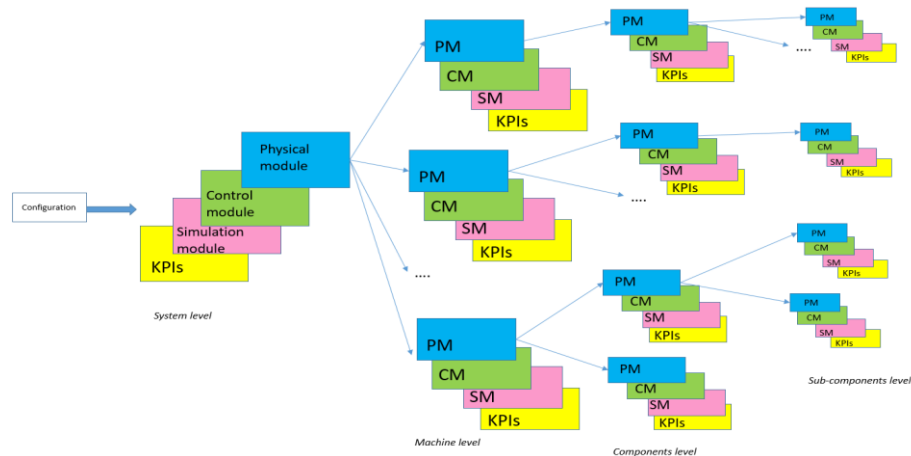


Fig. 1: Module-based view of configuration

The simulation module (SM). This module is the virtual representation of the physical module. As far as the simulation is a faithful representation of the real system, this module

may allow to evaluate the module as it would be in real situation. The replication of the real world in the virtual world could be a tricky process due to the complexity of the system. The idea of using modularity in real world could then be applied on the simulation model. Thus, the simulation model will be built modularly by adding or removing virtual module parts. We then assume that, each physical part of the system has its virtual representation. The simulation here can refer to mathematical models, discrete event simulation, energy consumption simulation, carbon footprint and cost evaluation.

The KPIs module. This is the measurement made either on the physical module or the simulation module or both. They allow to compare the real situation (or simulated situation) to the production goals, therefor a reconfiguration point. As KPIs depend on the use of the physical module, the module-based decomposition of the system allows to facilitate the diagnostic of each module. KPIs, as well as the simulation are not only related to the technical aspect of the system, but also concern any other measurement data that relevant enough to give accurate information about the system and or its component (depending on the level).

3 Case study

The case study presents how the module-based view of an assembly line can help to rapidly identify possible reconfigurations. Especially, we will show how the simulation module and the KPIs module help in the system diagnosis, and how the use of module simulation lead to the proposition of potential reconfiguration. The case study will be limited to two KPIs, the simulation used is the discrete event simulation with the software FlexSim©, and we will focus on the system and machine level diagnosis.

The example is an assembly line where products are transported on pallets. The product is a four colored disks arrangement. The current configuration is made of four (04) workstations named: ws1, ws2, ws3 and ws4 (ws stands for workstation). On ws1 a robot places the base on the pallet. On ws2 and ws3 an automatic system places the colored disk on the base, and ws4 uses a vision camera to verify that each color is well placed (the sequence of color is verified). The control logic of ws4 is the following: *if the product is non-compliant, it is from the system without being adjusted, even if the non-compliance could be easily corrected.* When analysing the assembly line performances, the production manager found that there is a high non quality rate.

The system analysing regarding the module-based decomposition and a simulation of the assembly line was built. It reveals that, the non-quality rate is due to the error on ws2 and ws3 (**Table 1**). Using the simulation model as a forecasting -previewing tool, the target then was to reduce the non-quality the assembly line (achieve the 100% quality), since the non-quality rate of ws2 and ws3 cannot be changed. By using modularity of the simulation module, many possibilities were tested by changing control modules of work stations, adding/removing workstations; obtained quality rate were compared with the target one. The simulated KPIs show that, even with error on ws2 and ws3 the quality rate reaches the 100% (i.e non-quality of 0%) is achieved by adding a workstations ws5 and ws6, and changing the control logic of ws4. Although the quality issue

seems to be solved, it would be more relevant to analyse the economical aspect of the proposition to ensure its feasibility.

This example shows how the module-based view, especially the use of simulation and KPIs modules could be used in the reconfiguration process. The example highlighted the fact that, the reconfiguration can either concern the physical aspect of the system (addition of ws5 and ws6), or logical changes (the added control logic to ws4). This is easily possible because the system has a modular structure as well as the related simulation model. The module-based decomposition of the system helps to clearly identify the problem, and to propose an accurate solution, without changing the entire system.

Table 1. Module decomposition of the assembly line

Level	module	Measured non-quality	Simulated non-quality
system	Assembly line	30-40%	30 – 40 %
Machine	Ws1	0 %	0%
	Ws2	-	5 – 10 %
	Ws3		5 – 10 %
	Ws4	0 %	0 %

4 Towards reference model to describe configurations

For a company, the reconfiguration management is not always an easy task. Finding and applying a configuration could be a waste of time and money especially if the searched solution is close to an already existing configuration. Thus, the ideal scenario would be to identify each configuration, to keep a history of different configurations used, and to store them in a database that can be used as a support for decision-making during the reconfiguration process. The reference model (**Fig. 2**) based on concepts of modularity aims to fit this target. The proposed model provides an overview of system needs, focusing on data and their interactions. The purpose of this reference model is to formalize the definition and description of a configuration, and to reach a generic database of configurations. The issues addressed by the model concern the following question: *What a configuration is made of? How physical modules are arranged and control within this configuration? Which product could be manufactured on this configuration, following which logical range? What are the KPIs related to this configuration?* As each manufacturing system differs from one to another they cannot be satisfactorily designed from pre-existing solutions. We do not pretend the proposed model will be a cure-all solution that will give an answer to all manufacturing contexts, it would be illusory. However, we believe that this objective becomes possible and realistic in the case of modular reconfigurable systems. Our proposition is therefore limited to this class of production systems. The proposed model is built using the UML class diagram (Unified Modeling Language). The main classes of the model are described below:

Module: it represents the set of physical, simulation, control and KPIs. It can refer to the system, machine or component level. The highest module is the system itself. Each module has related KPIs, which values can either be measured on the real system, simulated or required by the production manager. Comparing the KPIs values of each level of the system could lead to a reconfiguration decision.

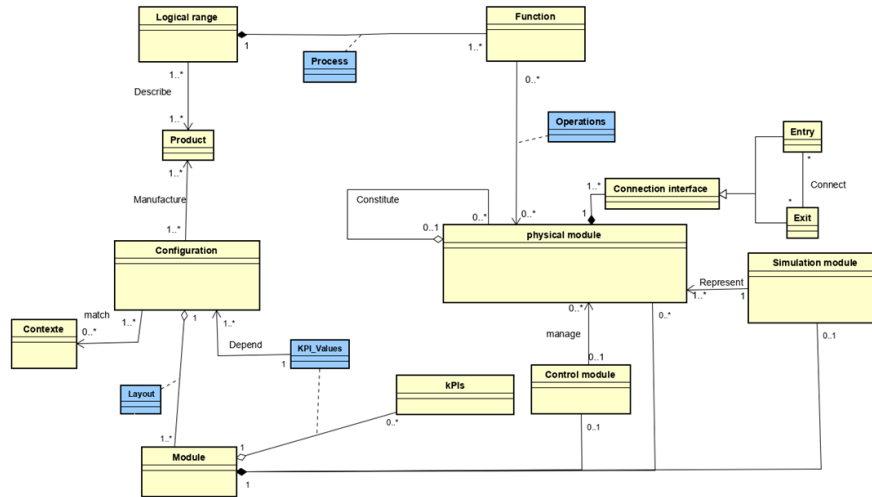


Fig. 2. Reference model of a configuration

Function: This class describes the services the system delivers. It represents the response of the system or a component when it operates under normal conditions and independently from the environment in which it is required [14]. When a function is assigned to a physical element of the system that consumes time and has a limited capacity, it becomes an operation. Thus, for the same system function, there can be several associated operations, i.e. several resources capable of performing the same function. For example, "Drilling $\varnothing=20\text{mm}$ " is a function in a system that can be assigned either to a CNC machine or to a traditional machine. Drilling $\varnothing=20\text{mm}$ by the CNC machine and Drilling $\varnothing=20\text{mm}$ on conventional machine are two different operations as operating time and other data related to the operation may vary. The function describes the capability of the system, while the operation describes how the function is performed by the system. From the management point of view, it is necessary to know for each configuration its potentiality. This information could be useful during the reconfiguration process, in particular when defining the reconfiguration strategy (i.e., how the system could adapt to a variation).

Product: This class describes the main element for which configurations are designed. A product is defined by a manufacturing process and could be achieved in different manner; different functions sequence so call logical range could be used to manufacture the same product. Thus, it is possible to know in term of functionality (functions and operations), whether a new product could easily be added to the system or not.

Configuration: This class represent the aggregation of modules, and could be related to a particular manufacturing context (the situation that triggers the reconfiguration process). Modules are arranged following a particular layout within the configurations.

5 Conclusion

The module-based view of the system at different levels has inspired the reference model proposed in this paper to describe a configuration. The module-based view of the system allows a quite precise decomposition and description of the system. That leads to a better knowledge of the system and its components. Note that this reference model gets align with some layers of the RAMI 4.0 (2nd, 3rd and 4th layer). Hence the proposed reference model could be seen as a part of industry 4.0 enabler. The case study shows how this module-based analysis of the system could be helpful in the reconfiguration process, especially the simulation and KPIs modules. Using the module-based view, we proposed a reference data model to describe configurations, the fact of including the simulation in the model is to align our proposition with the developing industry 4.0 paradigm. Moreover, we propose to take into account both technical, ecological (through energy consumption for example) and economical parameters while describing the configuration. The database obtained from this reference model would be rich in useful information and can easily be used as an input for the reconfiguration decision process. Indeed, the layout, the KPIs, the control module associated to each part of the system, and even the simulation data of the system could now be found in the same database. However, it is important to well define the level at which the decomposition must end: the greater the number of modules, the greater the volume of data, and the greater the time to put them together. The module-based vision permits an evaluation of a configuration “reconfiguration degree” aligned with the eight RMSs characteristics proposed in [15]. Thus it will be possible to compare configurations (in terms of characteristics) before choosing the best one. Future work will be to implement the model through a database, that will be used as an input of the reconfiguration decision process. As configurations can be considered in terms of the formation of holarchies [16], the module-based description seems to be quite similar to the holonic paradigm [17], a novel research issue could be to investigate an holonic description of RMS.

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