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Exploring the Synergies of Modularization, Interface Standardization, and Service-Orientation in Production System Simulation

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Abstract. Production systems of the future may be in constant flux and reconfiguration, continuously adapting to changing production conditions. Digital models and simulation are powerful tools that can be used for their design and operation. These models must co-evolve with the physical system to sustain their usefulness and relevance. This poses a significant barrier, given the complexities involved in their efficient creation and maintenance. To understand whether certain system design concepts make the simulation process easier, this study aims to investigate a combination of concepts that promote reconfigurability and flexibility to explore whether they can positively influence the simulation process. By integrating modularization, interface standardization, and a service-oriented architecture it is believed to support faster and easier creation and updates of digital models. Modularization enhances flexibility by decomposing complex systems into independent, interchangeable modules. Standardizing interfaces ensures uniformity and compatibility among modules. Using a service-oriented architecture entails the encapsulation of various functionalities within modules as services, which can be dynamically requested. Shedding light on the advantages arising from modeling and simulating systems adhering to the mentioned concepts the research also aims to lay the groundwork for further investigation into the potential synergies of these promising production concepts. The study's methodology includes modeling and programming of industrial robotic production modules adhering to predefined physical and logical interfaces. Interoperability and service orchestration are achieved through a service-oriented architecture. A simulated Manufacturing Execution System is integrated to facilitate handling of module services, product data and service requirements. Finally, a specialized software plugin was developed to support rapid module instantiation into a production system for evaluation. Results suggest that using a modular approach may ease modelling and simulation efforts and could be supported further by developing tailored tools for rapid system development.

Keywords. Modular production system, Simulation, Rapid model development, Industry 4.0, Digital Twins

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1. Introduction

Modularity, standardized interfaces, and service orientation are concepts that can be used to support the flexibility of production systems. Flexibility is an often mentioned desirable characteristic and can be described as the system's ability to be reconfigured and adapted to meet changing production conditions [1]. Within the Industry 4.0 (I4.0) production paradigm, it is often highlighted as an important key factor in achieving the paradigm's ambitious goals [2].

Two drivers for greater production system flexibility are the increasing demand for customized products and reduced product life-cycles [3]. If the products to be manufactured have highly individual requirements, the system may need to be ultra-flexible and undergo equipment and layout reconfiguration for each individual product [4].

To cope with frequent changes, production simulation can be used to design, commission, and recommission flexible production systems [5,6]. More specifically, simulation, as a tool in frequently changing production environments, can be used to both explore and design the system itself, as well as developing and testing alternative reconfiguration options and their feasibility and effectiveness in existing systems. Furthermore, an important utility of simulation is that the digitized system models can be used for development and optimization of the real control program of the system, without having access to the physical system. These two aspects make it possible to achieve a more mature solution for production system design or reconfigurations, thereby minimizing commissioning time and troubleshooting at later stages.

However, it is important to note that when a physical and a digital system are combined for the management and operation, a mutual dependence arise where they are both subject to changes that occur in the physical production environment. This requires both systems to be flexible enough for co-operation to remain relevant over time. Frequent changes in the physical production system then necessitate corresponding modifications to simulation models. Large alterations may even require full model reconstruction and redevelopment of control programs. This poses a significant barrier, given the complexities involved in the efficient creation and maintenance of digital models [7] and physical systems.

To meet the increased demands on future production systems, extensive research has produced and proposed a variety of architectures, tools, and technologies. It is likely that no single proposal will fully unlock the potential of these systems; instead, it will be the synergy between different approaches combined with simulation techniques that will be crucial to system development and operation. Therefore, it becomes important to explore specific combinations of approaches that could offer superior solutions for managing the flexibility demands in the simulation of production systems. Against this background, the assumption is made that future production systems are likely to be frequently reconfigured. To design such systems, several design principles and technologies will be integrated to achieve the desired flexibility. Simulation techniques will be used to develop, commission, operate and recommission these complex systems. As frequent system changes neccessitate modifications or reconstruction of simulation models the techniques to do this must be effective.

The primary purpose of this simulation study is to investigate the potential benefits on instantiating and updating production system simulation models when simulating a production system based on modularization, interface standardization, and service orientation. These design principles are usually considered as enablers for frequent changes and updates to production systems and the question we ask is whether this specific combination of concepts can extend its benefits to the simulation of such systems? Do these principles also enable frequent changes and updates to simulation models? This inquiry is explored guided by the objectives of developing a simulation built on standardized production modules, physical and logical interfaces, standardized module communications, a service-oriented architecture, a centralized manufacturing execution system (MES), and a dedicated software plugin for rapid module instantiation.

The subsequent details are organized as follows. Section 2 introduce the main concepts investigated in this study. Section 3 outlines the method and simulation creation. Section 4 outline the results which are discussed in section 5 together with study limitations. Finally, section 6 contain conclusions and future work.

2. Background

2.1. Production system simulation

Virtual engineering methods and digital manufacturing solutions such as simulation are mature and effective tools that can play an important strategic role in the design and optimization of reconfigurable systems [8]. There are several types of simulation that can be used for production system simulation. Four conventional simulation methods are Discrete Event Simulation (DES), System Dynamics Simulation (SD), Agent-Based Simulation (ABS), and Virtual Commissioning Simulation (VC). DES is a modeling technique that represents the operation of a system as a sequence of discrete events over time. This technique enables the exploration of higher-level system functionality, such as cycle times or product flows, through abstracted system elements. SD simulation is a continuous modeling approach that also emphasizes high-level system functionality, capturing intricate feedback loops and interconnections between system components, enabling the exploration of dynamic behavior and how various policies affect production processes and outcomes. ABS in production is a modeling approach that simulates the interactions and behaviors of individual agents, such as modules, machines, or components, within a system. By representing system entities, their relationships, and interaction rules, this method enables the exploration of emergent system behavior and the study of complex phenomena. All of these can contribute helpful information related to design strategies and concepts. However, the simulation technique that may have the greatest potential to provide an accurate representation of a system's behavior is the VC method [9,10].

VC modeling and simulation entail creating a virtual model and control system for a production system. The digital model mimics, through simulation, the dynamic and appearance of the physical system. In this way, developers can develop and work with the system without needing access to its hardware. Typically, this method has been used to develop and validate control programs before they are downloaded into the physical system, allowing the achievement of a more mature system solution that requires fewer errors to be resolved at later stages [11,5] and also facilitating more time-efficient commissioning and recommissioning [12]. In this way, the method can be a valuable tool in the construction of advanced production systems and the models created can also become part of, or develop into, a digital twin of the system [13].

However, every technology also has its barriers and currently VC is a resource-intensive activity that requires substantial investment and specialized knowledge as user-friendly methods for the efficient creation of simulation models are lacking [5].

2.2. Modularity

Products and production resources are becoming increasingly sophisticated, which is reflected in the growing complexity of production systems. Parallel to increased complexity, higher demands are placed on the system's flexibility in order to be able to quickly adapt to handle changing production conditions as well as coping with the production of a wide range of personalized and customized products which are increasing in demand.

Modularity can serve as a strategic approach to manage both complexity and increased flexibility in production systems. By breaking down complicated monolithic systems into smaller, manageable modules, the overall system becomes more understandable and comprehensible [14]. Modules are self-contained and can operate independently or be integrated with other modules into a significant number of different systems [14]. The individual modules can perform a limited set of encapsulated functions. They can be developed, programmed, updated or trained individually without disturbing the rest of the system. Once integrated into a system, modules must work together. This assumes that the modules can be seamlessly linked and interconnected which is ensured by standardization of the modules' physical and logical interfaces [15]. Physical standardization includes aspects such as using uniform connections or a fixed prescription for specific component dimensions and positioning, which ensures that the modules fit together physically. Standardization of the modules' logical interfaces means a detailed specification of protocols, signals and communication mechanisms. This combined standardization promotes seamless integration and interoperability between modules and enables rapid assembly of modules into coherent production systems.

However, even within a network of connected production modules with physical and communication infrastructure established, effective cooperation and task coordination are essential. These modules require a structured approach to produce products. One way to achieve this is the service-oriented approach.

2.3. Service-oriented architecture and product tracking

A service-oriented approach in manufacturing involves an established framework of service providers, consumers, and orchestrators. Service providers are production resources in the system that have their capabilities specified and encapsulated as services which are published in a service register. Service consumers within the system need these services to achieve their objectives. Consumers can, for example, be a machine, module, component, or product. They access services through an orchestrator that matches its needs with the available services in the registry and then participates in the invoking of the correct service to be performed. A service may consist of information-oriented functions such as generating or transferring scheduling information, product specifications, or service requirements, or production-oriented functions such as transportation or physical processing services [16]. A service provider can offer its services as simple base services or as combinations of these in the form of composite services performing larger functions; exposed services can in this way be dynamically matched and orchestrated with service consumers based on their specific needs [17].

As part of a service-oriented production system, the products produced are service consumers and are related to specific service needs, which may be unique to each individual product. The product and its unique service need information therefore need to be coupled. Utilizing technologies like RFID allows embedding information directly onto the product, allowing each item to store for example an individual identifier or its service requirements [18]. A product can either be encoded directly with information or linked to information stored in a database or production management system.

3. Materials and methods

3.1. Software framework

The simulation framework integrates a variety of components, as depicted in Figure 1. At its core, the framework uses an Integrated Industrial Simulation Software (IISS), specifically designed for the purpose of streamlining the modeling, simulation, and analysis of diverse industrial processes and systems. For this particular study, the chosen software is RobotStudio from ABB.

Furthermore, a data storage software is used for storing and transmitting data to the aforementioned software. While this storage can manifest as a database or a complex cloud-based system, it is noteworthy that this study primarily focuses on a more straightforward alternative using a versatile spreadsheet software.

Coordination between these two software components is achieved through the use of Python and the integration of the OPC UA server standard. Python, on the one hand, plays a key role in establishing a unified and coherent operational structure. While the OPC UA server creates a consistent and harmonious connection among the various software elements.

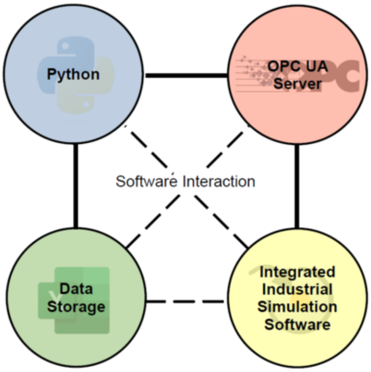

Figure 1. The interplay of software: solid lines signify direct interactions; dashed lines represent interactions mediated through intermediary software.

3.2. Modules

An important principle for planning and designing modules is the establishment and rigorous adherence to standardized physical and logical interfaces. All modules have a square shape with standardized dimensions and conveyors, which enable two inputs and two outputs for material and product flow, see figure 2. This ensures a physical connection when different modules are joined together. The way to link them together is simply to combine them in the IISS. Although the modules have some standardized features, its internal layout offers possibilities to vary robot placement and integrate additional equipment for module operation or customization.

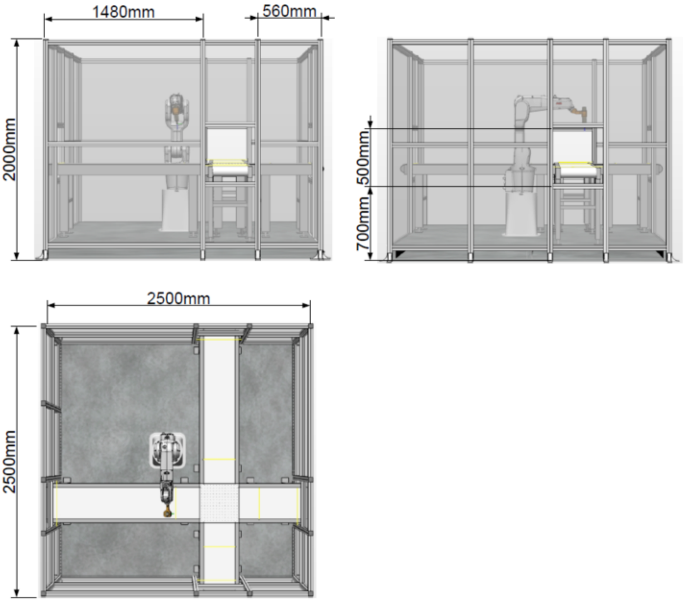

Figure 2. The standardized blueprint for modules with two material inputs and two outputs.

Logical interfaces are standardized for seamless interoperability between system elements. Common signals and communication mechanisms for inter-modular and MES communication allow ease of interconnection and interactions to request or provide services without unnecessary complications.

Module functionality is structured in a combination of basic services, often called micro services, and composite services. Composite services include at least two micro services. For example, a micro service can activate or inactivate a tool, while a composite service represents the complete action performed with the tool. Such a combination of micro services could be: ”Execute Path1”, ”Enable Vacuum Tool”, ”Execute Path2”, and ”Disable Vacuum Tool.” These combined services are indexed in a service register in the MES system where they can be linked to specific product types.

A fundamental feature of the system is the use of RFID tags to identify products. This identification makes it possible for each module, all of which have RFID readers, to identify products and request relevant information from the MES system about which service the module should perform.

New modules can be created from the generic standardized module. As the system is modular and standardized, they can be developed separately and then easily integrated into the simulation. Integrating a new module is a relatively straightforward process.

After the module is designed and programmed according to established standards, its service capability is listed in the MES system service registry. There, specific instructions can be set for the module, which define the services it will provide and the products it will handle. This central data storage ensures that the modules and system can be easily adapted to different production requirements.

3.3. Services and products

The service-oriented approach in this simulation study is based on the modules' encapsulation of functions as services and product types that need these services to transform into finished products. Both the modules' service offer and the product types' service recipes are stored in the MES system. The service communication process follows a specific mechanism, see figure 3.

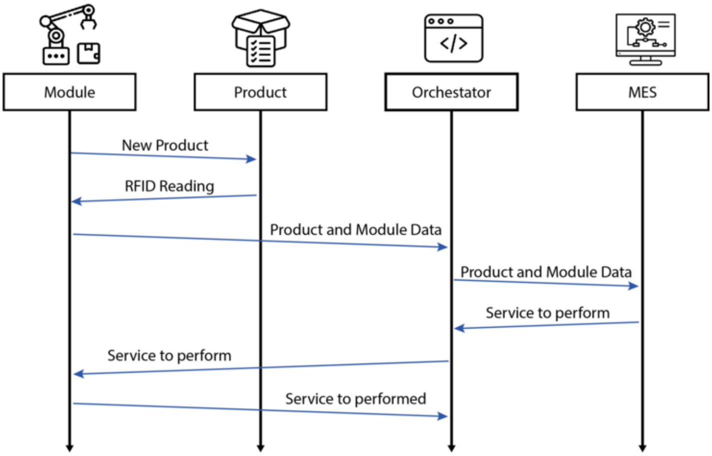

Figure 3. Overview of signal communication in the system.

An empty module indicates its status as being ready to receive a product. Similarly, a loaded module ready to send a product indicate this by a status change. This initiates a communication mechanism to manage the transfer of products between modules. Every product that enters the system has an RFID tag that contains information about its type. When a product arrives at a module, this information is read. The module then uses an information service in the orchestrator towards the MES system. This is where the product's needs are read and matched against the module's offer. Once the service that the product needs from the module is determined, the orchestrator sends the information back to the module. The module processes the product with the required service. Finally, when the product leaves the module, the module notifies the orchestrator of its empty status and readiness to receive another product to continue its operations. This communication mechanism ensures an effective synchronization between the simulation and the MES system, enabling smooth and coordinated operation of processes within the service-oriented environment.

4. Results

4.1. System instantiation

Based on the presented design choices, a modular production line simulation has been created in the RobotStudio IISS, illustrated in figure 4. The system consists of seven robot modules that perform the services of picking and placing, painting, gluing, palletizing, and material transportation. It produces two types of vehicle radio displays. In the first step, there is a painting station, where the product's casing is painted. A pick and place operation is then performed where a processor and battery are installed in the housing. After this step, both product types pass through a glue module. In this module, a robot applies glue around the casing perimeter. The product is then transported, based on its product type, to a module for installing the screen. Finally, production ends with a robot picking and placing the finished products in boxes for subsequent collection.

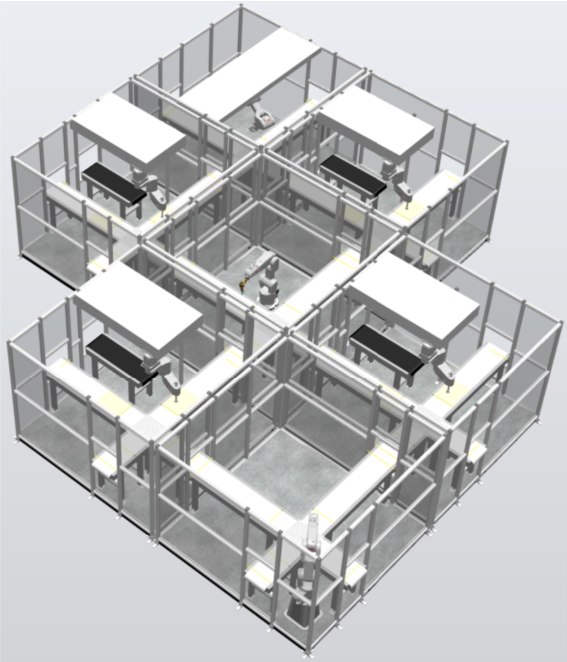

Figure 4. An instantiated system configuration.

To simplify the instantiation of modules into specific systems, a plugin was developed as a RobotStudio ADD-IN. This plugin allows rapid import of developed modules from a module library, eliminating the need for manual data entry and reducing errors. The plugin helps the user by visually prepositioning modules in a graphical environment, enabling easy adjustment and evaluation of placement, see figure 5.

Moreover, this plugin automates the connection of signals between different equipment such as modules, PLCs, and controllers in the simulation environment. In addition to being fast, a consistent and correct configuration of connections is ensured. Finally, there is a function for improving process visualization by easily showing or hiding ele-

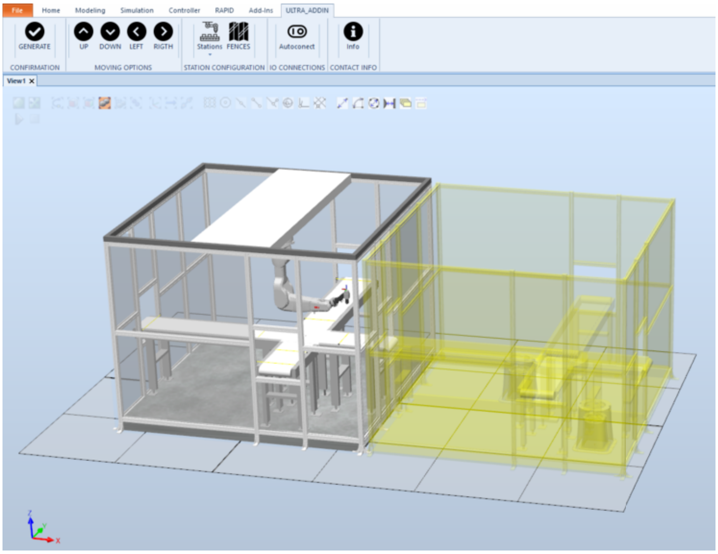

Figure 5. The plugin supports the user in positioning modules through a visual pre-positioning function.

ments that can obscure good visibility, such as fences and barriers. This contributes to a clearer representation of the workflow and interaction between system components.

After designing and instantiating the specific modules, registering their services, and associating them with product types, the system was able to simulate the simplified assembly of various vehicle radios, resulting in a successful production process simulation.

It is worth to highlight that the process of creating this simulation model was remarkably fast, intuitive, and user-friendly. The plug-in exploits the modules' standardized physical and logical interfaces for rapid positioning and configuration of connections, ensuring both speed and accuracy in model creation. The configuration of the modules' operation is quickly carried out by entering the modules' service offerings into the central MES system. Their operation is then controlled by the product communicating its service needs via the service orchestrator. This user-friendly approach significantly contributes to the accessibility and efficiency of using the simulation tool for various production scenarios.

5. Discussion and limitations

Simulation has been shown to have potential to add value when working with production systems. At the same time, there are clear challenges. One main challenge is the inefficient and resource intensive creation and maintenance of simulation models. When it comes to production systems that need to change frequently, which seems to be a trend with future systems, new or updated digital models may be necessary at the same rate. In order to investigate a flexible system design and its influence on the simulation process of the same, a simulation framework was created together with a software plugin tool.

As simulations are often associated with requiring significant resources, this study highlights a specific system type that might enhance simulation efficiency. If validated, the insight that certain system types may seamlessly integrate with simulation could impact decisions when formulating production strategies. The benefits of simulation for the design and operation of production systems might make it worth to design a system that more clearly enables the effective use of this tool to save resources.

Furthermore, given that certain combinations of production concepts can lead to improved simulation processes, specialized software could offer additional advantages. Such software can intelligently take advantage of the strengths of the design concepts, providing robust support to developers during the design, commissioning and reconfiguration phases. This is confirmed in this study where a software plugin was programmed to streamline the instantiation of modules into coherent systems. This leads to the question of open and closed software. There are both open and closed simulation tools available today. Open tools, which allow plugin programming, can be used by developers to tailor tools that leverage production concept simulation. However, proprietary software lacks this flexibility.

While the study suggests the possibility of simplifying the simulation process for production systems, the persistent problem of creating and maintaining the necessary digital models indicates that this is a difficult problem to solve. This study is limited by real-world factors not being integrated in the simulation process, such as project budgets, worker and machine safety, together with high levels of complexity, which significantly would affect the creation and use of digital models. Another important limitation of this study is that there is a lack of comparison between the approach used and alternative approaches. This could be a topic for further research.

Even though technology do progress, achieving usable digital models and simulations still demand a significant effort. This indicates that substantial progress is required before it becomes a straightforward matter.

Undoubtedly, many captivating visions of the future depict self-configuring cyber-physical and smart production systems that autonomously use simulation techniques such as digital twins. But the realization of this type of vision may reside far into the future and is likely to be a gradual and lengthy process. Initially, simulation technology must be developed to be sufficiently user-friendly and add significant value to justify integration into project budgets. Furthermore, widespread use would most likely precede autonomous systems independently performing advanced simulations. To this end, this study represents a humble contribution to this long-term journey.

6. Conclusion

Modularity, standardization of interfaces and service-oriented architecture are often pointed out as design principles that enable production systems that often have to undergo changes and updates. This study aimed to investigate whether this specific combination of design principles also brings advantages to the simulation process of such systems. By designing a simulation model based on mentioned principles together with the development of a software plugin that exploit their advantages, new simulation models could be quickly instantiated and executed. Therefore, we can reasonably argue that such an approach could potentially speed up and streamline the instantiation and updating of this type of simulation model. This is important given that simulation models for frequently changing systems must evolve alongside their physical counterparts to remain relevant.

This implies that in the pursuit of production systems that are constantly changing, the choice of design principles can play a significant role in how practical it is to also incorporate and use simulation as a tool alongside the physical system. Choosing a design path that enables continuous use of simulation can be of interest as this technology has great potential and is considered a key factor in managing future production systems.

Future research could explore alternative combinations of concepts to assess their effectiveness in streamlining the simulation process. Additionally, there is potential for investigating customized software solutions that leverage modular and flexible concepts, aiming to simplify the complexities associated with modeling and simulation.

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