SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220130

Reconfiguration Assessment for Production Volume Changes Using Discrete-Event Simulation: A Large-Size Highly-Customized Product Case Study

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Abstract. Globalization and mass customization are commonly translated into increased levels of complexity in manufacturing systems. One of the main reasons is the increased number of variables, parameters, and interrelations on the shop floor. This intrinsic complexity can grow exponentially when considering the manufacture of large-size products with high levels of variability and variants: the mass production of large recreational motorboats with high levels of customization and low production volumes, mass customization. With the increasing role of sustainability and concepts of Industry 5.0, focusing not just on improving production systems but also human wellbeing, quick decision making becomes essential. Data and digitalization are becoming the cornerstone for system improvement, and digital data availability and analysis can facilitate the utilization of computerized tools to support decision making and maximize the performance of complex systems.

For that purpose, simulation can be a powerful analytical tool to design, maintain, and improve complex manufacturing systems. Simulation techniques usually allow handling the size and complexity commonly associated with manufacturing systems. However, in systems with highly customized and large-size products, manual processes, and limited floor space, the implementation of simulation techniques is not straightforward, especially considering the aspects of variability, data collection, model validation, and system reconfiguration. With a particular focus on large-size products and limitations of a constrained existing facility layout, this paper presents the implementation of a simulation-based reconfiguration assessment considering manual production, assembly, and internal logistics requirements.

Going through an industrial case study of large recreational motorboats manufacturing, the paper analyses the system analysis, data collection, implementation, and validation of the methodology step by step. Considering different what-if scenarios, the focus is on the capacity reconfiguration using Discrete-Event Simulation. The results can serve as a guideline for decision-makers and stakeholders working with complex mass customization manufacturing systems and space-constrained facility layouts.

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Keywords. Simulation-based reconfiguration assessment, capacity analysis, reconfigurable manufacturing systems, large-size products manufacturing, changeability.

1. Introduction

Sustainability agendas and international competition are common issues considered as top priorities arising in manufacturing companies worldwide. An immense amount of time and resources are being invested in being able to handle these aspects. However, the decision-making process of managers and stakeholders, and the effective use of time and resources can be key role players in the future of these manufacturing companies. Several tools are commonly used to handle these issues, traditionally good planning, Lean Production, and computer simulation techniques [1-3]. However, the increasing complexity of the manufacturing processes, the limited availability of resources, and the digitalization revolution led by paradigms as Industry 5.0, make integrating computer tools in the decision-making process to improve the system and human wellbeing a must [4].

More recently, simulation software tools have commonly been implemented in manufacturing companies [5]. The use of Discrete-Event Simulation (DES) has been widely extended in big-size manufacturing companies due to the high levels of complexity and high numbers of variables and possible configurations of the system. Furthermore, the recent tendency to manufacture mass customization requires increased use of DES software tools and introduces the concepts of Reconfigurable Manufacturing Systems (RMS) [6]. RMS can be considered as systems designed for rapid change and adaptation.

Common uses of DES and RMS are system design, analysis, and improvement at strategic, tactical, and operational levels [7]. On the other hand, managers and stakeholders commonly focus on strategical decision making supported by tools such as value stream maps and analysis considering the Theory of Constraints. Combining these tools with DES to perform bottleneck analysis at a more tactical level, can enormously help identifying weaknesses of the system providing hints of potential improvements of the system at an operational level [8].

Considering big-size manufacturing companies producing big-size products usually implies low volumes of highly customized products, complex bill of materials, multiskilled human resources, and shop-floor space requirements [9]. This is translated into modifications on the factory shop-floor layout when applying changes in production, making space requirements a significant constraint in this kind of system.

This paper presents a DES case study to analyze the potential capacity and reconfiguration of the production system of big-size highly customized products. The case study is carried out in an international manufacturing company producing recreational boats, investigating how a simulation-based capacity analysis approach can contribute to reconfiguration assessments in large-sized and highly-customized products production. Specifically, the DES simulation model serves to highlight the potential bottleneck of the system at a tactical level by analyzing the use of resources. This bottleneck identification becomes an essential parameter for the reconfiguration of the system.

The paper is organized in the following way. Chapter 2 introduces a frame of reference of DES and RMS in manufacturing systems. Chapter 3 present the description of the simulation modelling process, including data collection, simulation methodology, and the proposed simulation model. Chapter 4 summarized the validation results and performed experiments. Finally, Chapter 5 presents the conclusion and future work of the project.

2. Reconfigurable Manufacturing Systems and Discrete-Event Simulation

The concept of RMS emerged as a need for resilience systems able to cope with demand fluctuations and production capacity changes more efficiently and economically [10]. This is achieved through reconfigurations, which can be understood as changes in the system's structure, components and software to address the mentioned challenges [11, 12].

Selecting the best configuration is one of the most important choices when designing and managing an RMS [13]. Reconfiguring a manufacturing system can involve areas such as the physical arrangement of machines and equipment, production planning and capacity changes, as well as the allocation of operators to different workstations as the requirements from a system change over time. The reconfiguration process of manufacturing systems is an essential key factor when production capacities or volumes changes are required [14]. However, using simulation to assess and determine how to reconfigure a manufacturing system is a complex task that requires a comprehensive understanding of the system combined with high modelling efforts [15]. Furthermore, the modelling effort of an RMS is affected by the abstraction level of the simulation model, which needs to provide enough detailed information to successfully understand the system's behaviors under the required test scenarios. Therefore, deciding on the abstraction level when modelling an RMS is a key aspect to consider during the development face.

On the other hand, simulation techniques are considered powerful and supportive when designing and evaluating manufacturing systems [5]. In a broad sense, simulation can be described as an imitation or replica of the operations of a real process or production system over time [16]. To facilitate the simulation process and computing performance, in DES models, the state variables only change at specific discrete points of time when significant events occur, resulting from activity times and delays [17]. For example, for every simulation model machine, these events can be the starting or finishing point of a machining process or transport, shift change, or tool change. DES is an essential tool for planning, operating, evaluating, and improving manufacturing systems [18].

Hence, simulation provides a better understanding of manufacturing systems and allows testing different scenarios over time for a set of input variables. This constitutes an advantage especially for RMS when they need to evaluate different alternative configurations. When it comes to RMS, DES can be a supportive simulation technique due to the variability and uncertainty found in this type of system [14]. Therefore, considering RMS's dynamic and stochastic nature, DES constitutes a suitable simulation technique to model this type of system.

Previous studies have used DES to support the design and management of RMS in different ways. Studies such as [16] and [19] have employed DES to model and analyze different RMS configurations. Such studies concluded that DES facilities the modelling process and the sequencing of the operations when comparing different RMS configurations. Differently, when DES becomes impractical due to the size and complexity of the RMS, modelling several different configurations becomes unattainable. This problem has been overcome in studies such as [20] and [21], combining DES and optimization enabling the advantages of both techniques.

3. Project description, data collection, and simulation modelling

As mentioned in the introduction chapter, the problem is based on an international manufacturer of recreational boats, whose products are also known as yachts or leisure powerboats. The range of products is quite broad, considering size and customization level. This case study focuses on the main production plant manufacturing three main product families. Looking at the production at a strategic level, the factory is divided into two main parts: composite stage and assembly, as can be appreciated in Figure 1.

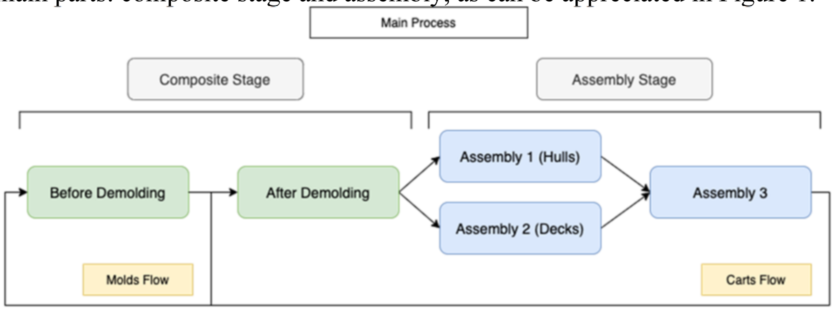

Figure 1. Conceptual model of the manufacturing system at a strategic level.

In this figure, both main stages of the production, composite and assembly, are each subdivided into two sub-stages, before demolding and after demolding; assembly 1 + 2, and assembly 3. This first division can be easily appreciated on the factory shop floor; however, the second sub-division cannot be easily appreciated. The sub-divisions have the main goal of highlighting the milestones for the takt time. This means that the entire production process can be considered to have four main general stages: The part before demolding, the part after demolding, the first part of the assembly, and the second part of the assembly. The key here is that time to perform those processes should be similar to reach a smooth production flow. Nevertheless, this takt time is different for the main three product families being manufactured in this plant. This increases complexity considerably when the product models share the same processes and stations in the composite stage.

To stay competitive today, manufacturing companies aim to produce quality products that can meet customer needs and respond to variations in demand caused by quick changes in the market. To reach this goal, products must be produced faster and delivered to the market in short timeframes. To achieve this, it is crucial to know the production capacity of the production plant and how it responds to changes in production planning. A great tool to face these problems is the use of simulation. As previously mentioned, simulation can be used to analyze systems configurations more accurately with possible scenarios and help in the decision-making problems regarding the profitability of new investments. However, a great deal of data and knowledge are required for building a simulation model.

One of the main steps in a simulation project is model translation or construction. However, in many cases, more time is required for the understanding and construction of a conceptual model of the system. This conceptual model has to represent the system to be simulated. It is crucial to clarify the data collection process, identifying which processes have to be modelled, their interrelations, which data is necessary, which data is available, and which data is not possible to collect. In this case, there was no data available of the manual process (most of the processes in the production line). Therefore, interviews and observations were performed at the factory to obtain estimations that then were double-checked with experts and verified with the management team. Figure 3 shows the conceptual model of the system at what is considered tactical level in this project. This conceptual model should be represented by three main flows representing the different processes of the three main families of products manufactured in this factory. However, they have been summarized in one flow, having some customized processes or pathways passing through operations that are not needed depending on the product model.

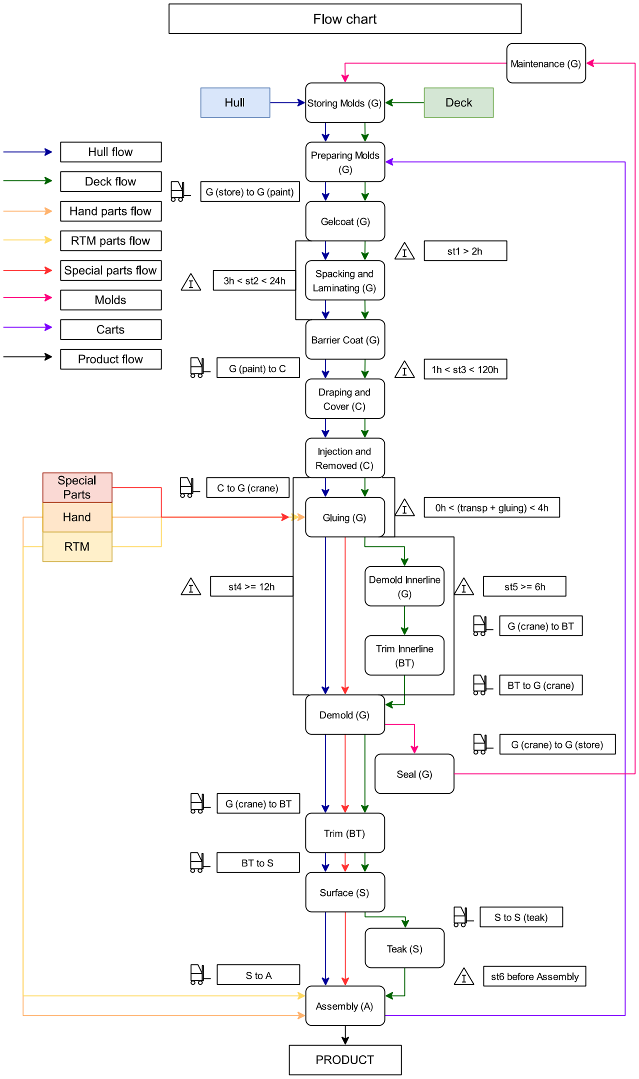

Figure 2. Conceptual model of the system at a tactical level.

After processing all the information gathered in the previous steps to build the model, this conceptual model is translated into the simulation software tool to develop the simulation model of the system. The collected data of the different processes and products are also introduced n the model to reflect the reality of the factory as accurately as possible. Figure 4 shows all the processes on the shop-floor layout of the factory represented in the simulation model.

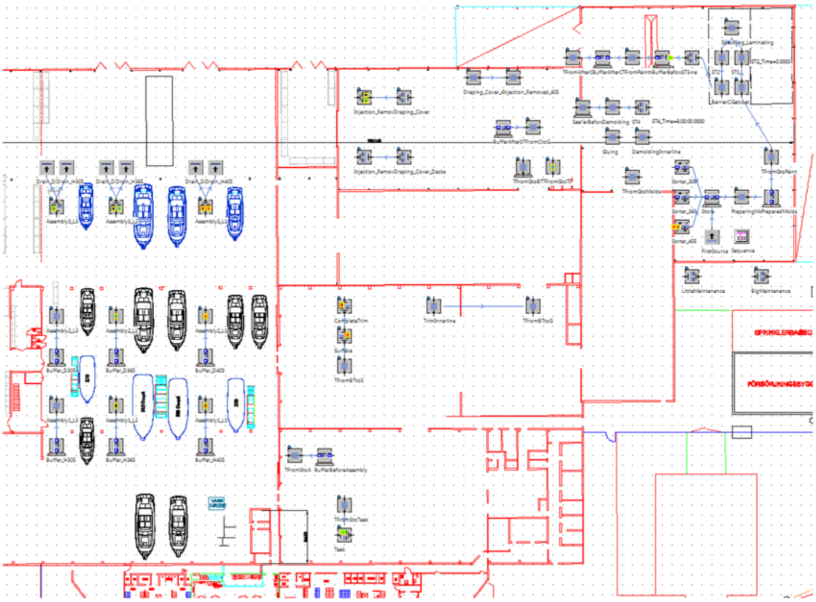

Figure 3. Discrete-Event Simulation model of the manufacturing system.

The left part of the figure shows where the assembly stage takes place, the three main assembly lines for the three different families of products. The central- and right parts of the figure show where the different processes of the composite stage take place. In this project, the simulation software tool chosen is Siemens Tecnomatix Plant Simulation. It was chosen due to its powerful graphical representations and customization possibilities with programming. Nevertheless, some previous expertise in the use of the software tool and programming is required.

Once the conceptual model and the collected data was introduced into the simulation model, it was time for the verification stage. Verification is a determination of whether the computer implementation of the conceptual model is correct [22]. Therefore, the conceptual model in Figure 3 and all the data introduced in the simulation model, were double-checked to ensure they were introduced correctly in the simulation software tool. To perform this verification, some meetings with the managers and stakeholders of the project were organized. In these meetings, different parameters about variants, products, and processes were revised; in some cases, some adjustments had to be done to represent reality accurately. A set of assumptions was also created and discussed to ensure every simplification or modification of the simulation model did not affect the accuracy of the model. Once the model was verified, the next natural step was the validation of the model. This is presented in the next chapter accompanied by the validation results.

4. Validation results and experiments

Once the simulation model has been constructed and verified, to be able to trust the results it produces, it is necessary to validate it. Validation is to ensure that the output parameters and logical structure of the model represent the real system in an accurate manner [22]. For this purpose, the results obtained from running the model during one simulated year were compared with the real results, the historical data of the plant over one year. Table 1 compared the data from the real system "Factory", with the results obtained from the simulation model "Model", for the three different families of products.

Table 1. Validation results obtained from the simulation model, compared with the data from the real system.

	Throughput (products/year)		Lead Time (days)		Work in Progress (products)	
Product Family	**Factory**	**Model**	**Factory**	**Model**	**Factory**	**Model**
A	45	42	25	22	12	8
B	35	32	29	31	6	6
C	20	22	44	45	6	6

The validation results obtained show that the existing difference is considered reasonable for the purpose of this study and the collected data. A coefficient of variation of 38% was applied in the original simulation model and proposed scenarios to represent the human variability factor. After the verification and validation processes of the model, the results obtained doing experiments, or "what-if" scenarios, can be then compared with the original simulation model presented above. In these what-if scenarios, different modifications or hypothetical configurations of the system and resources can be tried, for example, to analyze the performance of the main output variables of the model: Throughput (TH), Lead Time (LT), and Work In Progress (WIP).

First, an initial bottleneck analysis was performed with resource utilization statistics to analyze the possible limitations of the system. This method is based on the utilization of the different machines or processes, being one of the most common approaches in industry; however, detailed analyses along time are required to avoid bottleneck shadowing by dynamic or shifting bottlenecks [23]. This first bottleneck showed that the assembly lines of the system did not seem to be a limitation of the capacity of the system. Analyzing these results with the management, it was clarified that the assembly process is quite flexible due to having separated lines for the different families of products. Therefore, the focus was put on the composite stage. Secondly, a bottleneck analysis considering just the composite stage was performed. Figure 4 shows the bottleneck analysis of the composite stage, in which the percentage of the time the main processes are occupied is highlighted in green.

For the generation of the results, DES was employed to model different RMS configurations. These configurations were included in two main scenarios that represent and reveal the performance of the system under different reconfigurations. Since most of the processes are manual processes, the green part in the chart includes other sub-tasks such as setting up, failed, stopped, and paused. As it can be appreciated in the figure, the processes included under Painting Hall, show to be the main bottleneck of the system. After this second bottleneck analysis, three main what-if scenarios were defined. According to estimated demand increases for the coming years, the first scenario consisted in modelling a configuration of the system that could handle increasing the TH of product families A by 25%, B by 16%, and C by 22%. The simulation model showed

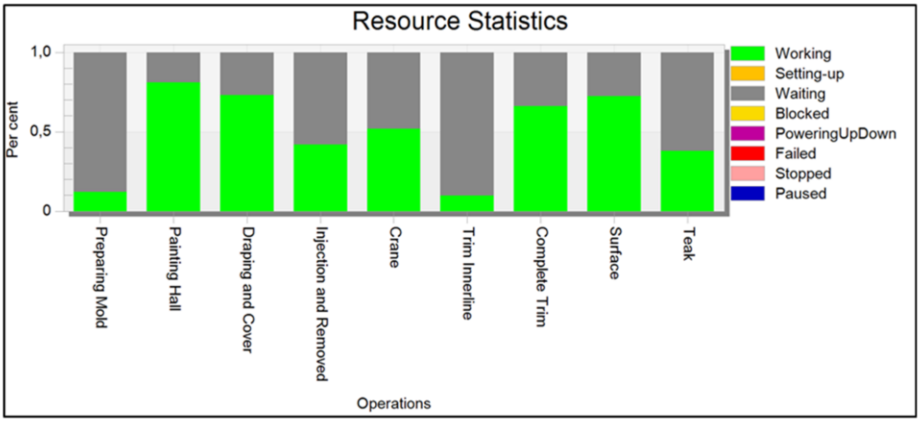

Figure 4. Bottleneck analysis highlights the occupation of the main processes at the composite site.

that this scenario would be impossible to implement in reality without improving or duplicating some of the processes in the production line. Even if prioritizing product A at every process, it was not possible to reach the proposed throughput increase with the defined system configuration.

The second scenario aimed to analyze the reconfiguration of the system to increase the production just of product family C, prioritizing its production, considering the production of families A and B could be reduced up to 30%. In other words, what would be the configuration of the system to maximize the production of product family C, with the possibility of reducing the production families A and B up to 30%? Having all the knowledge and information of the system in the simulation model and the engineering team, this second scenario was defined by trying different configurations of the system in different what-if scenarios. With the best scenario, the results shown in Table 2 were obtained.

Table 2. What-if scenario results comparing Scenario 2 with the original simulation model.

	Throughput (products/year)		Lead Time (days)		Work in Progress (products)	
Product Family	**Original Model**	**Modified Model**	**Original Model**	**Modified Model**	**Original Model**	**Modified Model**
A	42	36	22	28	8	5
B	32	35	31	29	6	4
C	22	34	45	32	6	5

This second scenario shows a significant improvement of more than 50% in the TH of product family C, increasing in 9% the TH of product family B, and reducing in 15% the production of product family A. Hence, according to the model, the total TH of the factory could be increased by 9%. This solution was double-checked with the management team and its feasibility was approved. This capacity increase reconfiguring the production plan would be translated into 9 products more per year without adding resources or changing the layout.

Nevertheless, the methodology to perform this scenario was time-consuming due to the high number of what-if scenarios to find a better system configuration. Additionally, the simulation expert required a great deal of expertise in the system; something that can be limiting if the simulation expert has no previous knowledge about the system or constant support from managers and stakeholders. This solution could be improved with the integration of optimization in the methodology, and a more detailed level of abstraction simulation approach in the identified bottleneck.

5. Conclusions and future work

This study proposes a simulation-based capacity analysis for reconfiguring large-sized and highly customized system RMS concerning changes in the production volumes. This study employed DES to synthesize the production system's understanding and represent the different considered scenarios through a detailed simulation model able to reveal critical information for reconfiguring the production system.

The Key Performance Indicators (KPIs) considered were TH, LT, WIP, and the utilization of the resources. These KPIs served as performance indicators of the systems when facing the studied scenarios. The scenarios studied considered changes in the capacity of three families of products and the reconfiguration possibilities of the processes and production plan to increase or reduce the production of the three families of products. The DES bottleneck analysis identified the main limitation of the system and helped to analyze the reconfiguration capacity of the system considering different product families.

The finding of this paper concludes that DES can efficiently support the reconfiguration assessment needs of large-sized and highly customized productions especially considering the bounded time for decision-making in this industry. Moreover, the DES approach used provides a graphical visualization of the process which facilitates the analysis. This graphical visualization can contribute to reconfiguration assessments in large-sized and highly-customized products production.

On the other hand, it is also true that the procedure can become tedious and time-consuming when considering several possible configurations of the system. For example, a more detailed abstraction level of the main bottleneck, the painting process, is not easy to simulate quantitatively. Further research about bottleneck identification and improvement is therefore required at a more operational level to be able to integrate the approach in a solid RMS methodology.

Future work includes the integration of optimization in the methodology followed in this project. Additionally, a more operational abstraction level of the bottleneck analysis to analyze its impact on the reconfigurability and resilience of the system can be included. In this case, the Functional Resonance Analysis Method is proposed to analyze the process in a qualitative way considering variables such as operator skills, interruptions and process availability.

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