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Simulation-Based System Improvement with Work Domain Functional Analysis: A Large-Size Product Manufacturing Case Study

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Abstract: Manufacturing companies worldwide have recently experienced challenging times due to a lack of staff, materials, and components. This has mainly been caused by abrupted logistics chains and collateral effects of the last pandemic situation. Ideally, resilience engineering systems, systems that have recovery capacity from difficulties, are prepared to overcome changes in demand and disruption in production. However, lack of flexibility, adaptability, and available digital data limit the implementation of resilience systems. To overcome this problem with a high number of interrelations considering human-machine interactions, a methodology including Discrete-Event Simulation, Work Domain Analysis, and Functional Resonance Analysis Method is proposed to design, analyze, and improve complex manufacturing systems. These tools allow deeper analysis of the interrelations of the system at different abstraction levels and both with quantitative and qualitative perspectives. Going through an industrial case study, the aim is to increase the capacity and resilience of a leisure-boat manufacturing company producing highly-customized large-size products, which adds additional constraints to the problem. The objectives are to increase flexibility and productivity at the same time as maintaining high-quality product standards. The results highlight the identification of some constraints of the system such as the main production bottleneck, lack of space, and a limited number of transports, molds, and skilled personnel. The implementation and results of the methodology have proved to serve as a decision-support tool, providing insight about limitations of the system to managers and stakeholders, as well as a guideline for increasing capacity and resilience of the manufacturing process.

Keywords: Discrete-Event Simulation, Functional Resonance Analysis Method, Capacity Analysis, Resilience Systems, Manufacturing,

1. INTRODUCTION

Manufacturing is considered the secondary economic sector within the three-sector model in economics (after the extraction and production of raw materials, and before service industries). The increasing competition in the global economy makes manufacturing companies constantly aim to increase the efficiency of their systems with computational tools (Ganzarain Epelde et al., 2019). System optimization, globalization, and fierce completion might reduce the resilience of manufacturing systems. Resilience is usually defined as the capacity to recover from failure or difficult times or situations. In the last two years, the interdependences of manufacturing factories worldwide have been extremely affected by disturbances in the production and logistics chains upstream; many of those disturbances starting overseas and with long and complex transport networks between raw materials and final costumer. One of the main reasons has been the recent Covid-19 pandemic causing border and travel restrictions, quarantines, lockdowns, collapsed systems, and sick employees and employers. That has been combined with disturbances in logistics chains, especially within the transport industry of logistics containers.

In many cases these disturbances have caused major production stops, affecting throughput, lead times, and production costs. Lacks of stocks, increased delivery times and product and transport costs have become normal during the pandemic. The impossibility of quick recovery and the lack of resiliency of the systems have significantly affected entire national economies. Three of the main major problems that could have been key preconditions for this are:

- The outsourcing tendency in the last decades in which suppliers and factories were moved abroad, relying on steady logistics chains which increased cost was compensated by lower production costs.
- Extreme system optimization without room for adaptation, highlighting Just-in-Time and storage minimization.
- Lack of resilience production able to handle the variations in demand and capacity.

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The supposed robustness of the logistics chains of a significant part of the manufacturing world has been demonstrated to be a weak link in the production chain with disastrous consequences (De Vet et al., 2021). This has also been aggravated by the temporary unavailability of personnel due to Covid-19 imposed restrictions, quarantines, and sickness; highlighting the difficulty of finding replacement skilled staff.

Nevertheless, luxury markets tend to be less affected by economic crisis, for example, the leisure-boat manufacturing company involved in this research has seen an increase in demand for its high-end products during the pandemic, something unexpected by the production management. This problem has been aggravated by the issues highlighted above. Therefore, this paper analyzes the implementation of the Work Domain Analysis (WDA) and the Functional Resonance Analysis Method (FRAM) for qualitative system improvement in combination with the quantitative approach of Discrete-Event Simulation (DES). Going through an industrial case study, a methodology combining DES with WDA, FRAM is proposed for increasing the resilience of the system, focusing on a key human-machine socio-technical system, the painting and molding process of the boats, analyzing its capacity and flexibility. This paper first introduces a frame of reference of DES in Section 2 before introducing the approaches of WDA and FRAM and the followed methodology in Section 3. Section 4 summarizes the results and discussions of this case study and Section 5 presents the conclusions of the project.

2. FRAME OF REFERENCE, DISCRETE-EVENT SIMULATION

Quantitative system improvement tools are usually demanded in manufacturing. One well-known quantitative tools for system design, analysis, and improvement is simulation. Simulation is an analytical tool that can serve to design, maintain, evaluate, and improve systems using a virtual representation over time (Banks, 1998). Modelling can be considered a disciplined, scientific, and rigorous procedure based on observation of dynamic phenomena, hypothesis analysis, and data collection methods, commonly with the purpose of system design, evaluation, and improvement (Ganzarain Epelde et al., 2019).

The combination of unfortunate events presented in the Introduction section has made management teams of many manufacturing companies come back to the powerful capability of analyzing hypothetical “what-if scenarios” with simulation tools. However, socio-technical systems considering complex human procedures are not easy to model, not always there is available data, and not everything can be easily quantified to be translated into the code of a simulation software tool. Some authors propose the use of Systems Dynamics (SD) to support decision making, to cope with dynamic complexity when working with qualitative data, especially at strategic or management level (Ganzarain Epelde et al., 2019). However, this kind of model at strategic level requires a systemic view or a holistic view of the whole system to understand the non-linear interrelationships of the entities to be analyzed (Ganzarain Epelde et al., 2019). This is translated into an exhaustive data collection process of the whole system including qualitative and quantitative data.

Some authors propose an interactive problem-solving process using the Lean tools for quality improvement in the leisure-boat industry (Henriksen et al.; Rolstadås et al., 2012). However, to consider detailed capacity analysis, product mix, and changes in product demand, focusing on the quantitative data analysis, DES can provide major benefits. DES compromises a specific kind of simulation representing a system that changes only at a discrete set of points in time, meaning that a simulated clock of the software tool records the times when each event occurs in the simulation model (Banks et al., 2005). These events can for example be the arrival of a product to a processing machine or the departure time for a transport to deliver some parts. Usually the main objective is to design and analyze possible configurations of the system, however, when quantitative methods start presenting some limitations, a combination with qualitative methods might be necessary.

At the beginning of this industrial case study, simulation could be one of the main tools for the improvement process, since quantitative data was available for the different processing times, buffers, and product mix and transports information. Therefore, simulation was evaluated as the right tool to work with a capacity analysis of the system. Four main steps were defined for developing the DES model. First, the required data was collected and analyzed in parallel with defining a conceptual model of the system at an operational level (including the level of detail of different departments, transports, and processes required to manufacture each family of products). Second, this conceptual model was translated or represented into the simulation model with the simulation software tool as presented in Figure 1.

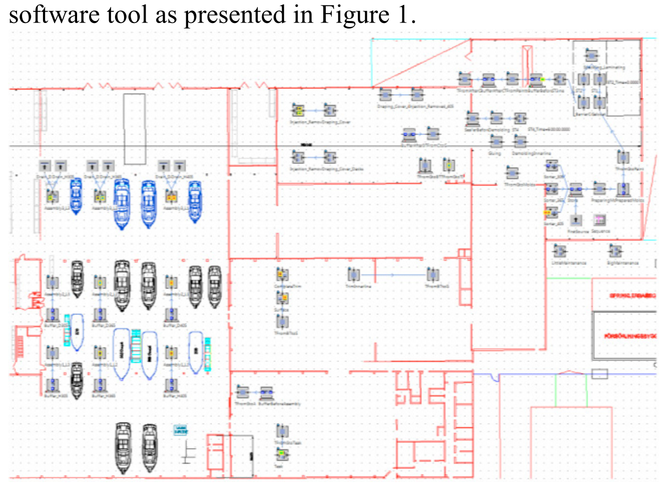

Figure 1. Discrete-Event Simulation model of the production layout.

The simulation software tool used was Siemens Plant Simulation. It was selected due to the customization possibility with programming of the predefined objects or processes of the simulation model, useful to represent complex system characteristics, behaviors, and interrelations. The middle and right parts of the layout represent the production or machining areas, and the left part of the model represents the assembly area. Each grey squared object represents a process, such as trimming, painting, transport, store… At this stage, additional required data might be identified when building the model, therefore, additional data collection and analysis have to be planned. In the case data is not available, assumptions can carefully be made. An example is to interview the people involved in the process to try to build a triangular statistical distribution with the minimum process time, average time, and maximum time. This distribution has to be validated by experts of the process before programming it in the simulation model.

Once all the processes relevant to the project are represented in the simulation model, the time horizon and output variables have been defined, and the model is properly running, the third step is to verify and validate it. Verification can be considered as checking the system represents reality as it is, while validation is to ensure the behavior and performance of the simulation model represent the real system in an accurate manner (Banks, 1998). This is usually done in coordination with the experts and managers of the different areas of the system represented in the simulation model. The validation process can be done by comparing the output variables of the simulation model with the main parameters of the real system considered for this study: throughput, lead time, and work-in-progress. Fine-tuning of the input parameters of the simulation model was done until the comparison looked accurate enough for the purpose of this study. Having a running verified and validated DES simulation model of the system means it can be used as a digital twin or digital copy of the system to test different scenarios.

The fourth step is analysis and experimentation, to evaluate changes in the design or performance of the system with "what-if scenarios". In this project the focus was on the capacity and flexibility of the system; how many products could be manufactured per year considering different combinations of the demand of three main product families. To obtain some data about the hypothetical scenarios, several modified versions of the original simulation model were programmed and a quantitative analysis of the performance and occupation of the different processes were analyzed in each case. The main contributions of these scenarios were to investigate different margins of the product mix and a bottleneck analysis to analyze the main limitations of the system. The bottleneck analysis of the original simulation model is presented in Figure 2. This chart represents the occupation level of the main processes of the system included in the production or machining stage.

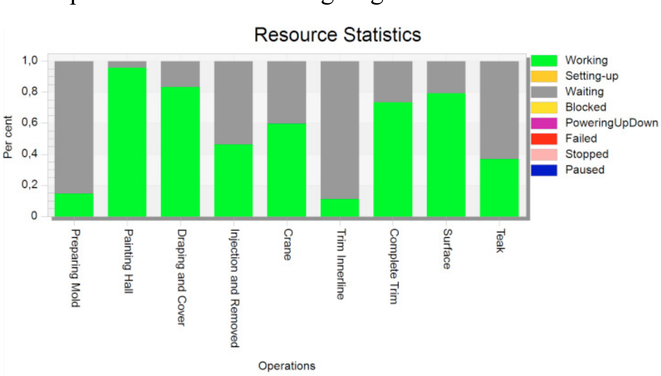

Figure 2. Bottleneck analysis of the main manufacturing processes.

In this chart, higher levels of occupation can be appreciated in the Painting Hall, Draping and Cover, and Surface processes. After some meetings with the project and management team, the decision was to focus on the painting process to try to improve what seemed like the main bottleneck of the system. The painting can be considered as the main process, since it usually includes different layers of paint, gel, and coating on the mold that makes the structure of the deck, hull and different parts of the boat. However, when focusing on the Painting Hall, the processes of the painting seemed quite trivial. Quantitative data was inexistent and affected by many factors not directly related to the painting process but affecting performance. Additionally, due to the high-quality standards required with the painting process, the processing times could not be considered for reduction; adding another painting cabin was limited due to space constraints. Therefore, the focus had to switch at this point from the quantitate analysis of the painting process to the qualitative analyses with FRAM and WDA to analyze the deified bottleneck. The concepts and proposed methodology are described in the following section.

3. WORK DOMAIN ANALYSIS AND FUNCTIONAL RESONANCE ANALYSIS METHOD

Variability, stochasticity, and complexity are common attributes of sociotechnical systems. The design, analysis, and improvement of this kind of system are usually addressed by fundamentally limited deterministic and probabilistic approaches (Patriarca et al., 2020). Cognitive engineering, usually related to the analysis, design, and evaluation of complex sociotechnical systems, englobes the concept of WDA: A form of Work Analysis identifying the functional structure of a human- or automation- controlled system (Hollnagel & Woods, 1983; Vicente, 1999). WDA techniques are especially useful for complex sociotechnical systems; it can be a great tool recommended to describe processes and constraints of a work system (Naikar et al., 2005). WDA has been widely applied in several disciplines combined with the FRAM method including systems improvement in manufacturing and risk prevention nuclear power plants (Černetič & Blatnik, 2005; Hugo, 2001; Sawaragi et al., 2020).

The FRAM can help to represent and understand the behavior of these socio-technical systems by analyzing complex processes and interrelations with visual aids representing objects, relations, and their assigned variability. In different domains, it has served as a tool for analysis and validation of epistemic actions and methodologies in large and complex systems (Hirose et al., 2021; Patriarca et al., 2020). Epistemic actions can be used to reduce the memory, time, and probability of error of agent-internal computation (Maglio & Kirsh, 1996). Therefore, analytical tools not exclusively dependent on quantitative methods are also necessary.

In this methodology, a combination of DES with WDA, and FRAM is presented. A methodology can be considered as a logical set of steps and methods linking assumptions of a system to perform a study (Säfsten & Gustavsson, 2020). In this research, the methodology followed a case study method with a design and creation research strategy (Oates, 2005). The methodology is presented in Figure 3, defining the processes highlighted in black color as generic for the entire project, in blue color with a focus on capacity analysis and qualitative data, and green color with a focus on quality performance and quantitate data.

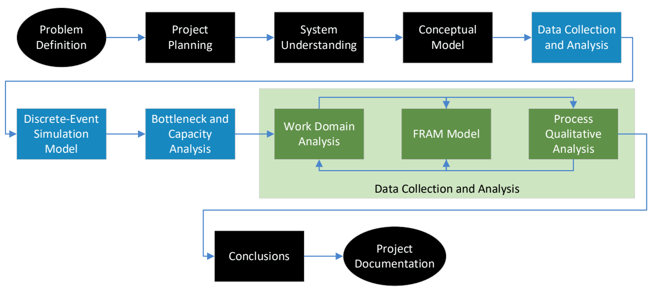

Figure 3. DES, WDA, and FRAM improvement methodology.

Starting with the initial black items represented in the methodology, the first natural steps to follow in this kind of system improvement are the identification of the problem and the definition of the objectives of the project. These steps are key to understanding the size and complexity of the project and accordingly defining the project team and project plan. The project team should include experts in the different areas of the project and should consider vertical integration, including from managers to operators. This is important to make sure all perspectives of the problem are considered to help the project team understand the whole picture of the system and to visualize its possible target conditions or potential improvements.

Secondly, to understand the whole picture of the system, knowledge is required at different abstraction levels, such as strategical level (the broader perspective usually focusing on the entire system and top-management decisions), tactical level (focusing on mid-management and production or assembly departments or areas), and operational level (focusing at the operator and process characteristics of the manufacturing system). Thirdly, to gain this knowledge, a conceptual model of the system at these three different levels can be a good approach. A conceptual model of the entire system including transport, processes, and flows of materials and products can help to narrow down the scope of the project and to focus the resources and improvement approaches on specific parts of the system. For this purpose, the Lean tool of Value-Stream Mappings can be of great support if there is some Lean knowledge or expert in the system or project team (Uriarte et al., 2017). Flowcharts and diagrams can also be used for this purpose.

Continuing with the blue items in Figure 3, the diverse project team is key to define the conceptual model of the system and collecting and analyzing data. A study of the required data, available digital data, and an estimation of the data that could be collected should be done at this stage. This study should be considered in the project plan, allocating enough time to it. It is usually a time-consuming activity due to the common lack of available digital and organized data in manufacturing systems. This data collection and analysis process can also be done in parallel with the translation of the conceptual model into the simulation model.

Once the data is collected, the DES model can be built. As explained in Section 2, it consists mainly of the translation of the conceptual model into programming code with the support of the simulation software tool. This simulation software tool can be chosen depending on the availability, budget, and existing expertise. The obtained simulation model has to be verified and validated before its use for system analysis, what-if scenarios, and capacity analyses.

Hereafter, entering the area of the methodology highlighted in green in Figure 3, the FRAM was selected as one of the main options due to the powerful understanding and representation capability of variability associated with human-machine sociotechnical systems, such as the painting processes being analyzed in this case study. An initial FRAM model gave some insight regarding possible causes of the identified bottleneck of the system, the painting process.

Some authors argue about the order of implementation of the WDA and FRAM processes. It is believed that first implementing WDA and then FRAM can be more enriching to obtain hidden interrelations of epistemic actions, therefore, this idea has been respected in the prosed methodology. However, in this case, a preliminary draft FRAM model was defined to visualize possible processes and interrelationships that should be further analyzed in the WDA. Then the FRAM representation was refined with the insight of the WDA. Therefore, these three processes of WDA, FRAM, and Process Qualitative Analysis are considered an iterative loop in Figure 3, guiding in parallel the data collection process.

The quantitative data previously collected for the DES model was not enough to model such a qualitative process, having a strong focus on the quality of the painting process and having just the process time to paint a product. Based on the insight from a draft FRAM of the production processes (Fig. 4), a new data collection process had to be done to obtain tacit knowledge of the painting process.

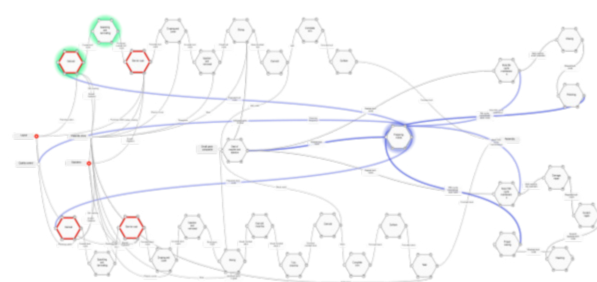

Figure 4. Functional Resonance Analysis Method of the system.

The FRAM representation of the production systems considered the entire production or machining stage area of the factory. The data collection was based on observations, interviews, and documentation analysis, to find the main critical process steps that represented the system, its interrelations with the staff and processes outside the painting module as well as inputs and outputs of materials, products, and transports of other departments. Special attention was paid here to the interrelationships of the objects in the model to identify epistemic actions, especially with skilled staff being able to handle the variability of the processes represented in the model. Each of the hexagons in the figure represented a process or transport such as gel coating, spackling and laminating, barrier coating, transport, or maintenance. Connections representing inputs, outputs, resources, control, or time variables were made between the hexagons or

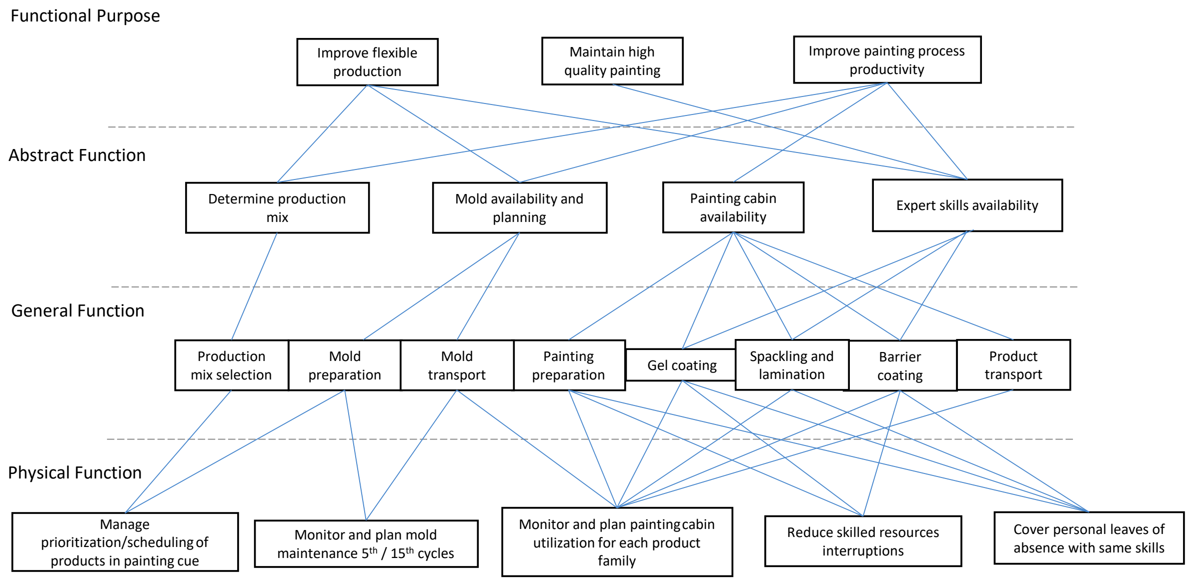

Figure 5. Work Domain Analysis diagram of the painting process.

processes to represent flows of materials and information. This representation was double-checked by the project team to ensure it represents the real system in an accurate manner.

Working with the FRAM representation it was clear that DES could not provide further data at this stage, specially to model or study further interrelations. A deeper analysis was required to analyze and model the variability of those functions and interrelations. Therefore, the analysis tool of the WDA was utilized to obtain a clearer picture of the missing knowledge and qualitatively analyze the previously identified bottleneck with DES. The aim was the system improvement by understanding the bottleneck and identifying its “hidden” abstract functions and relationships with other parts of the system, keeping in mind three main objectives: To increase the flexibility of the process, maintain the high quality of the products, and improve productivity.

The WDA focuses on a function unit or subassembly unit of the entire manufacturing system, excluding other departments and areas outside the Painting Hall process since it is exclusively focused on the painting. The data for building this WDA was partially extracted from the previously constructed simulation model, completing that data with qualitative data regarding further descriptions of the processes through interviews with personnel in charge of the painting process, managers, and stakeholders. To represent the WDA, a stratified four levels abstraction hierarchy has been utilized to represent the different functions of the painting process and its direct interrelations with the three mentioned main objectives. It is represented in Figure 5.

The first level of abstraction, Function Purpose, represent these three main objectives: Improve flexible production, maintain high-quality painting, and improve painting process productivity. The second level represents the Abstract Function, focusing on the key aspects affecting the three main objectives. The Abstract Function identifies four aspects related to the main objectives on the first level of the WDA. The importance of available skilled staff is highlighted here due to their valuable tendency to make fewer mistakes, backtracking, and redundant actions (Maglio & Kirsh, 1996).

How these aspects are related to the main processes is represented by the connections with the lower level, the General Function, This General Faction abstraction level, defines the main steps of the painting process itself. This third layer is connected with the Physical Function layer, identifying which variables and parameters of the Abstract Function and Functional Purpose are critical to the performance of the processes summarized in the General Function. This WDA serves as a guideline for the data collection of the FRAM representation. It also identifies the main aspects to focus on when looking in detail at the improvement of a process with a high level of variability, several interconnections, and considering sociotechnical factors usually just appreciated by expert operators.

Implementing this methodology using DES, WDA, and FRAM as described here can provide useful insight regarding the system. Especially when considering capacity analyses, system reconfigurations, and what-if scenarios that can generate relevant insight for managers and stakeholders as the conclusion of the project to support decision making. These DES and FRAM models as well as the WDA have been useful tools for the company or system in question to keep working with system improvement and to use them as a guideline for similar system improvement projects. The main results of this case study are described in the next section.

4. RESULTS AND DISCUSSION

The results of the DES model, the WDA, and FRAM have identified specific parts of the system limiting production and identified key variables in which further analysis and actions are required to make the system capable to adapt and increase productivity while maintaining high-quality standards. Going through the proposed methodology it has been demonstrated that DES can be a good approach for firstly performing quantitative analysis, followed by an iterative FRAM modelling and WDA loop to improve a system when the analysis of more qualitative aspects is required. At a strategic level, looking at the wide picture of the manufacturing system, DES has provided relevant insight for managers and stakeholders regarding capacity management and flexibility, being able to analyze the behavior of producing different types of products and analyzing the limitations of the system. Further analyses with the WDA allowed drawing the "why" and "how" of those critical interrelations of the painting process, identifying key variables such as maintenance and transport interruptions affecting performance.

More specifically, some of the results analyzing the FRAM representation reinforce the importance of understanding and controlling the interrelations between the maintenance department and the painting department. Since all the molds used for shaping and painting parts of the products have to do cycle maintenance every 5 and 15 cycles, sometimes the performance of the painting process is affected due to delays or lack of skilled personal. It has been identified that waiting times for maintenance are generated due to a lack of maintenance and product mix planning as well as skilled experts' availability. Usually, the staff working with the painting of the products are not aware of the maintenance procedures, especially in the case of non-expert employees. Additionally, the interrelations of the transports of the molds, also necessary to move the parts of the products to and from the painting cabin, were also limiting the painting process, especially considering that the number of molds and transports is limited due to space restrictions and specific to every boat model and product part.

5. CONCLUSIONS

System improvement and analysis usually require a structured way of working to manage complexity, especially when the size of the system is considerable. System improvement usually implies several factors, variables, constraints, and objectives, something that can be understood as quite related to simulation approaches. In this paper, a system improvement industrial case study has been presented with a methodology combining DES, WDA, and FRAM to analyze and increase the capacity and flexibility of the manufacturing system. Going through the literature, it is not common to find manufacturing industries applying this combined approach.

DES has served as a great support tool to identify weaknesses of the system at strategic and tactical levels, nevertheless, at operational level there not always is available quantitative and digital data, especially when considering epistemic actions and tacit knowledge. To overcome that problem, this combined approach of DES, WDA, and FRAM allows considering large and complex systems without requiring extensive operational-level data-collection procedures, to then narrow down the problem to specific parts of the system in which limitations of the system at operational level can be identified. It can support the decision-making process and increase the resilience of the system with different levels of disruptions, such as major logistics chains disruption and lack of materials, components and personal lacks to improve the overall performance and readiness of the system.

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