DISCRETE EVENT SIMULATION PROCEDURE TO BUILD THE PRODUCTION DIGITAL TWIN OF HIGHLY AUTOMATED AND COMPLEX PRODUCTION SYSTEMS

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1.- INTRODUCTION

Current economic conditions and manufacturing environment are characterized by increasing uncertainty and complexity, factors that will determine the design of manufacturing systems of the future. The complexity of the production systems can be seen in the following features [1]: 1) greater variability of product, 2) shorter product life cycles, 3) variable product routing, 4) minimization of the lot size, 5) flexibility in equipment and processes, and 6) advanced automation and smart control systems.

In the face of these needs, manufacturers and suppliers of advanced solutions in the area of discrete manufacturing point out as critical elements for the manufacture of the future digitization, the simulation and automation, both at the level of equipment and complete lines. These solutions consist of single equipment units, the elements of manipulation and their control systems, in order to provide a complete solution to a product (e.g., automotive tires, railway axles). Complex manufacturing systems are managed with high level control systems, which make decisions, control manufacturing orders and monitor the behavior of the different components and machines.

The manufacturers of these turnkey manufacturing systems need to consider all these factors in the design of the complete solution, for which they make use of different simulation tools. Discrete event simulation (DES) suits well to the simulation of complex production environments [2],[3] and can be used as a tool for validation of the design from the productive point of view.

However, the use of simulation and the construction of the digital twin go beyond the design stage of the solutions. The manufacturers of these systems are immersed in a strategy of servitization [4], with the aim of providing products and services that will enable them to offer differentiating solutions to customers throughout the life cycle. In this context, the production digital digital twin will offer services focused on production improvement during the use stage of the facility.

The digital twin joins the virtual world with the real system, using the digital technologies promoted by Industry 4.0 initiative. While the term is receiving increasing attention from industry and academia, the concept is relatively new for the academia. This article focuses on the production digital twin and provides a procedure for building the digital twin based on discrete event simulation, for complex and highly automated production systems.

The article is structured in the following manner. Section 2 reviews the state of the art related to the production digital twin and its main components. In Section 3 the procedure for the development of the production twin is described. Section 4 presents a use case, related to the digital twin of an automated line for production of railway axles. Finally, section 5 shows the conclusions of the work.

2.- STATE OF THE ART

In the last few years the use of terms such as the Digital Factory, Industry 4.0 and Digital Twin have significantly increased both in industry and academia. The concept of Digital Twin combines the technologies of the Digital Factory and Industry 4.0, linking the virtual world and the physical world. It begins by defining the Digital Twin, to proceed then with the deployment of the different elements that make it up. Among the different definitions of the Digital Twin [5] since its first use by Grieves in 2003, this article will use the proposal by Stark [6], which states that "a digital twin is the digital representation of a unique asset (product, machine, service, product-service system), that alters its properties, condition and behavior by means of models, information and data". The elements of the Digital Twin according to [6] are the Digital Master, the Digital Shadow and their linkage (Fig.1). Conceptually, the Digital Master would be related to the Digital Factory, which is based on the software tools and methodologies that allow to design, simulate and optimize products and their production systems [7]. The second major element of the Digital Twin is the Digital Shadow, composed of operational data collected by Industry 4.0 technologies (among others OPC-UA, Big Data) [8,9,10]. The Manufacturing Digital Twin allows to simulate and optimize the production system to increase competitiveness, productivity and efficiency [10].

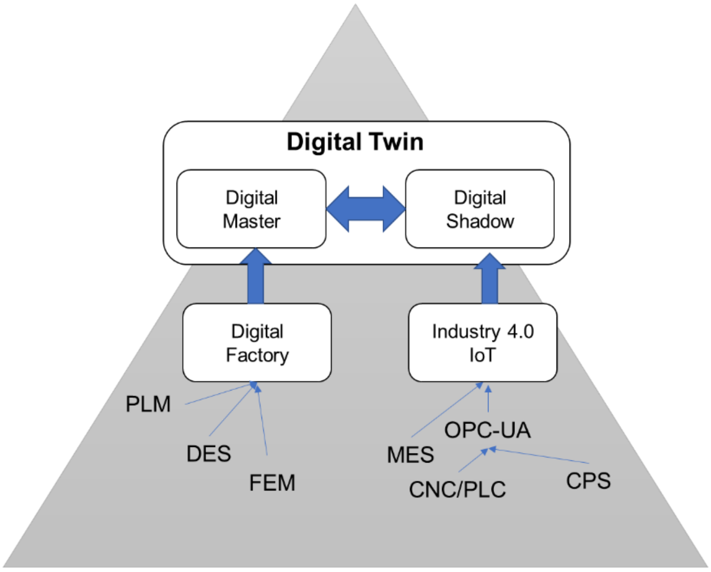

Fig. 1. Digital Twin concept. Own elaboration based on concept [6]

Simulation is a key element within the Digital Twin. Among simulation tools, DES is a technique oriented to production and logistics, with applications such as: validation of productive concepts [11], improvement and optimization of productive flows [12], production planning and control [10]. Simulation based optimization allows to find the optimal or nearly optimal solution in the case of conflicting objectives. In the literature there are publications that show the benefits of combining the simulation with optimization [3,12], using evolutionary heuristic as genetic algorithms.

The level of detail of the simulation depends on the scope and objectives to achieve. For simulations at a high level (at a systemic level, interfaces between plants, production networks), some authors propose the aggregate modeling [3], in order to reduce model development and data collection times. The detailed modeling allows to describe more realistic behaviour, although with an increase in time and cost [13]. The DES modeling proposed in this paper refers to detailed modeling, where model scope would be from a manufacturing cell until a whole plant.

One of the problems for the use of DES has been the time and cost spent on collecting input data [14] and the quality of the data [15]. Senington [16] proposes a linked data approach for the automatic extraction of data and information to feed plant simulation models. Precisely, the Digital Twin is based on the connection between the real data of the physical system and the digital model, performing this task in an automated way.

As a result of the state of the art, it can be concluded that the concept of the Digital Twin combines technologies that were already used in isolation, highlighting the connectivity and its automation. This article contributes to state of the art in proposing a methodology for the development of the production digital twin, going into depth on the detailed discrete event modeling, and concludes with the demonstration of a use case.

3.- DISCRETE EVENT SMULATION PROCEDURE TO CREATE A DIGITAL TWIN

This section details the procedure to build the production digital twin. The procedure has been divided into 3 stages: 1) definition of the scope of the production digital twin, 2) development of the digital master, 3) development of the digital shadow. Stages 2 and 3 can be performed in parallel.

Defining the scope of the digital twin

At the operational level and within the framework of each project, the project development team must define the scope of the twin digital, which shall include: (a) definition of the functionalities of the digital model, (b) definition of the features of the digital shadow, variables and indicators to monitor and display, data sources (e.g. PLC, CNC, MES), (c) automation in the data connection between the digital model and the real system. This stage is critical for the development of the later stages.

Development of the digital master based on DES

The digital model should represent the real production system**.** For this purpose, a classification of the elements to be considered in a detailed modeling for highly automated solutions has been developed (Table I). The selection of these elements has been based on the main objects identified in turnkey solutions in discrete systems. For each of the items some issues have been listed. For example, for the handling equipment element, most common configurations are included, such as robots, gantry cranes, automated guided vehicles (AGVs) and conveyors. The logic that determines the interaction between the handling equipment and one or more of manufacturing equipment units should also be modeled in detail.

In this work it is proposed to integrate the development of the DES digital model within the solution development process. For that purpose, the simulation engineer should interact and be integrated within the design, process and automation teams, enhancing the collaboration among them. In fact, the development of the digital twin implies a systems engineering and collaborative approach from the very beginning and among the different participants.

The role of the different teams is described below. The process team provides the flowchart with the operations to be performed as well as the timing information (cycle times, load times), information on production loss parameters (e.g. tool changes, part reference changes, equipment breakdown) and necessary resources, for each of the equipment units and required operations. The design team provides the layout of the solution. The automation team provides the control and logic of the handling systems, by focusing on detailed aspects such as the priority of different operations or the algorithm that determines the movement to be carried out by the handling element. Different strategies of handling can have a significant impact on the performance of the solution, therefore the DES model is presented as a very important tool to validate the control logic.

The first use of the digital model lies in the design and development phase of the solution. However, the development of the digital twin to provide services for the customer implies productizing the model, creating the interfaces and making appropriate modifications for the model towards user-friendliness and usability, fulfilling the intended functions.

Development of the digital shadow

The digital shadow is created by gathering information from the machine controllers and sensors in the operation phase. The digital shadow comprises the history and traceability of the real system, as well as its connection to the digital model. In the design phase, automation and data engineers must define the variables to acquire and monitor from the different devices and integrate them into a platform for data acquisition, considering also how these data will be transformed and displayed to the user. One of the advantages to the solution providers is that the automation engineers can have more control and access on the variables to monitor in their machines. In addition, the variables that will be used to feed the virtual model should be defined, as well as the connectivity with the model.

Item	Attributes and controls for modeling
Part	– Bill of material/product structure. – Definition of each component and its variants. – Definition of types of part failures and their probability (quality and inspection). – Part routing.
Manufacturing Equipment	– Automation level of equipment: manual, semi-automatic, automatic. – Cycle times by part. – Breakdown parameters, intervals and duration of breakdowns (preventive and corrective maintenance). – Configuration parameters: capacity, load/unload time. – Set-up times, part to part time matrices. – Tool consumption, that can be a function of the equipment and the part (different tools and consumptions per part at the same equipment). – Energy consumption.
Handling equipment.	– Types of material handling equipment: robot (with one or more grippers), linear gantry (with one or more portals), gantry crane of area (with one or more grippers), AGVs, conveyors,… – Configuration parameters: capacity, load/unload time, speed, energy consumption.
Control	– Production Planning and control. Batch sizes. – Logic of the elements of manipulation. – Management of handling request – Control of equipment states. – Control of the state of manufacturing orders. – Collisions and traffic control.
Organization of Production	– Manufacturing orders. – Shifts, calendar and resources. – People.
Structure data	– System layouts: Layout of machine elements, handling and buffers.

Table I. Classification of elements to consider the detailed model DES

4.-CASE STUDY: RAILWAY AXLE MANUFACTURING LINE

As a demonstration of the production digital twin a line for the manufacturing of railway axles is shown, which includes the following operations of the axles: identification/marking, manufacturing (turning and grinding) and non-destructive testing (NDT). This line has been developed by a machine tool manufacturer located in the north of Spain that offers complete and automated solutions. The line has been represented in Fig. 2 and is composed of 6 equipment units, entrance conveyor, exit conveyor, a linear gantry and a single buffer each of the machines.

The main tools used for the development of the digital twin have been Tecnomatix Plant Simulation for the digital model, Facts Analyzer Evoma for multi-objective optimization and Savvy Data Systems as acquisition and digital platform. Connectivity with the digital model has been achieved by an interface with the digital platform that acquires real plant data, transforms these data and makes them available to the digital model.

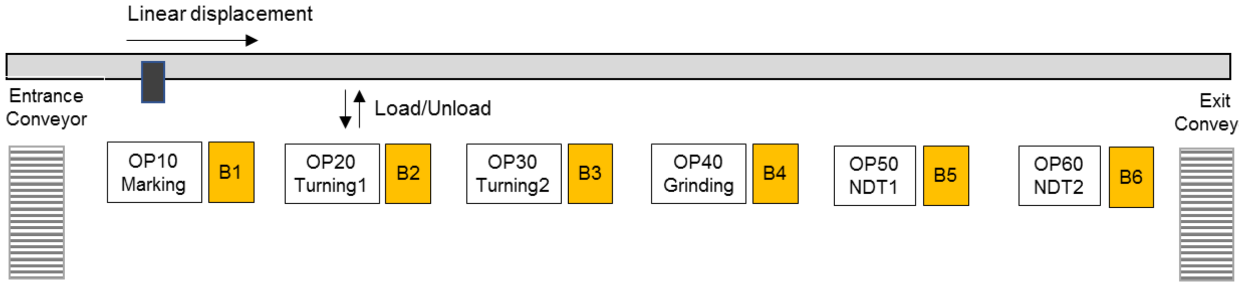

Fig.2. Schematic design of the line

Concerning the characteristics of the manufacturing line, it follows unidirectional flow, although not all references have to go through all operations (each reference may have its own routing). The shop orders are received from the planning system of the company and batch sizes are variable (between 10 to 50 units). The line allows dynamic change-over, which means that a machine can be in set-up state while other machines are still in operation. The digital model based on DES has replicated the operation of the line, modeling in detail the logic of the gantry system.

The control of the gantry system sets out the requirements for the execution of the movements, assesses the state of the origin and destination equipment, assigns priorities to the potential movements and, finally, commands and controls the execution of movements. The flow diagram that determines this logic is shown in Fig., while Fig. 4 displays the programming in the modeling tool and the simulation interface. Modelling in the simulation tool is done through the development of custom objects that reflect both the flow of material as the behavior (using variables and methods).

The digital model was developed during the detailed design stage of the line. The team that participated in the development of the model was composed of process, design, automation and DES technicians, which allowed for a better understanding for the definition of the solution.

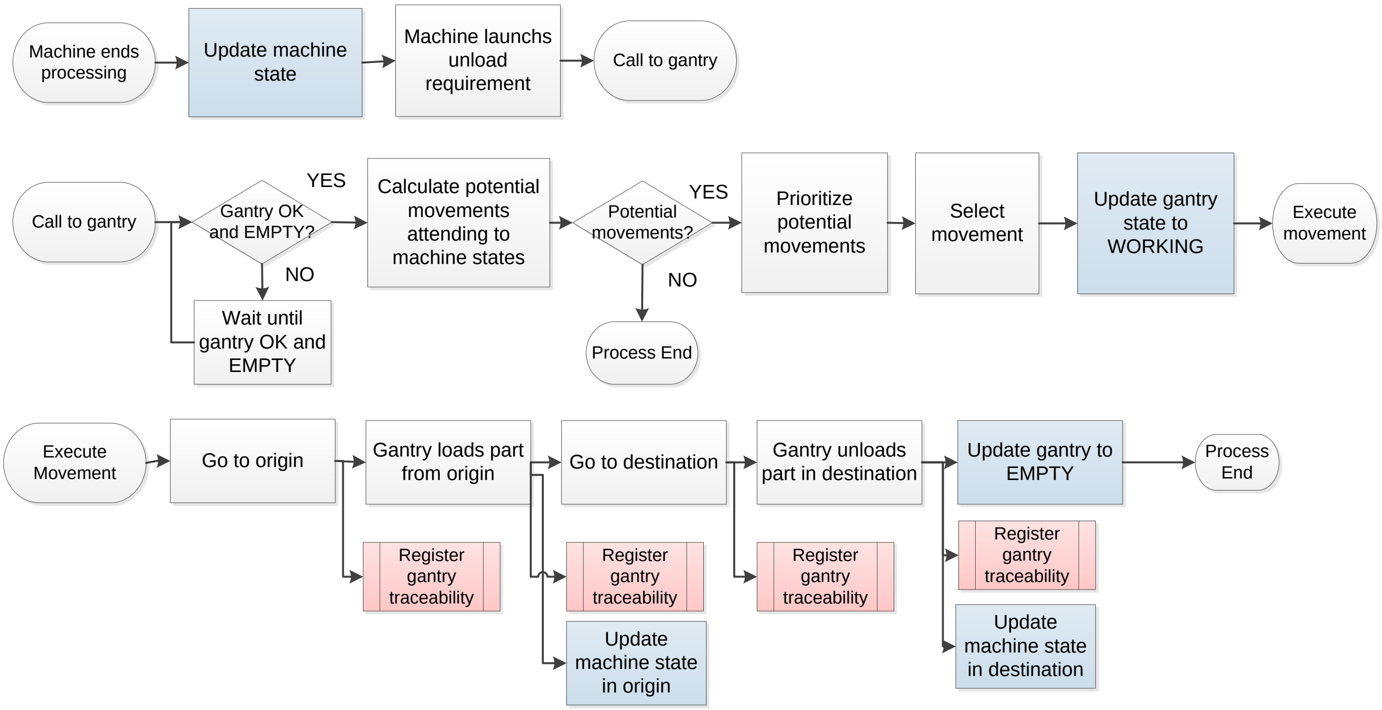

Fig.3. Flow diagram of the gantry control after unload requirement

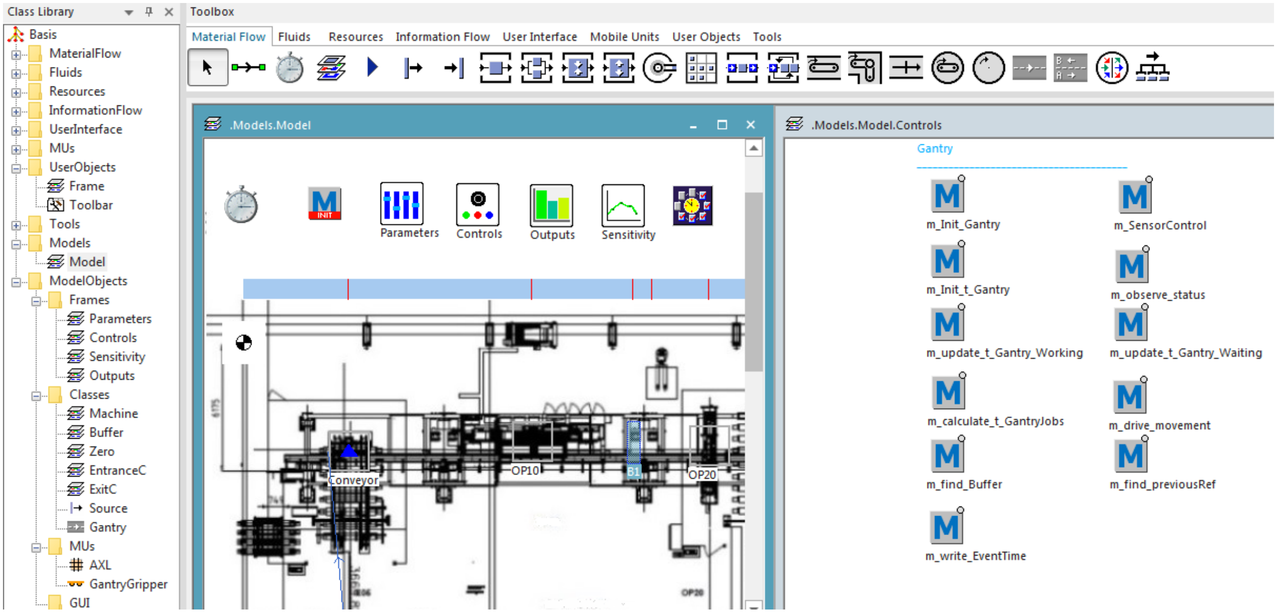

Fig. 4. Tecnomatix Plant Simulation interface and elements for the control of the gantry

The first use of the digital model was the design validation in contract conditions. The model was simulated during a year of production, and there were 5 replicas, in order to validate compliance with the requirements of production in stochastic conditions. A sequence of input axles according to customer specifications was simulated, with 5 references (estimated percentage for the mix of the references) and a lot size of 25 units.

In addition, the simulation was complemented with an optimization analysis, in order to determine what would be the most effective improvement actions to increase production. For this purpose, Facts Analyzer optimization tool was used. The optimization objectives were: maximize production, minimize the effort in changes and minimize the total number of machines to modify. The decision variables for the model are shown in Table II. The multiobjective optimization method was NSGA-II algorithm, there were 5000 evaluations of a simulation of 10 production days, with population size 50 and number of replicas of 3. This optimization model was performed by associating a generic cost/effort to each change parameter, but it could also be performed using cost/investment data for each type of change in each of the machines to be included in the analysis.

A Variable	**A description of the value**	**Basis**	**Min**	**Max**	**Effort/cost to change**
Availability	Absolute value of 100	97	97	99	From 97 to 99 -> 100
Process Time	Portion (on a per unit basis) of the current value of the process time	1	1	0.8	From 1 to 0.8 -> 100
Handling time	Reduction on the current value (in seconds)	0	0	10	From 0 to 10 -> 50

Table II: Decision Variables for optimization

Optimization results are presented here. The range of solutions was from 400 to 515 produced units, with a maximum of 6 machines to modify. Once all possible outcomes were displayed, Pareto front solutions were filtered. Using the advanced filtering option, the maximum number of machines subject to modification was reduced to 2 and for this case, the best of the solutions provided a throughput 25.7% higher than the base case.

In addition, during the development of the automation the variables to monitor, PLC tags and CNC signals were defined. The monitored data were analyzed in the digital platform, so the customer has the traceability of the production, the process and some other features, what is called the digital shadow. The link between the data in the digital platform and model was performed using the API provided by the digital platform, where part process times have been collected and aggregated by part type to automatically feed the simulation model. In particular, the model can automatically receive the distribution of the processing time per axle, mean times of changeovers and an estimation of technical availability.

5.- CONCLUSIONS

This article proposes a methodology for the development of the production digital twin, going in depth in the detailed modeling based on DES. The production digital twin combines the DES simulation and Industry 4.0 monitoring technologies. It provides production system manufacturers with a design and validation tool for the manufacturing solution, as well as a product service to include in its portfolio to customers. For customers, the production digital twin is a tool for planning and improving the operation of the production facility in use phase, a valuable function to manage production systems in uncertain environment. The article concludes with a use case of the production digital twin of a line for the manufacturing of railway axles.

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