The Digital Twin as a Design Tool in Industry 4.0: A Case Study

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***Abstract*— This manuscript reports the findings of a study conducted in a manufacturing assembly plant that is in the journey of incorporating Industry 4.0 technologies on its production floor. In this manufacturing company, some manual operations will be replaced with painting robots, because of that, a digital twin was created to quantify the influence of them. Specifically, during this investigation, the influence of the buffer size over the proposed manufacturing system with painting robots on it was quantified. This study demonstrates the relevance of the digital twin as a design tool that one can employ to plan a gradual transition from a classical manufacturing production floor to a modern production floor with Industry 4.0 technologies.**

Keywords- digital twin; discrete-event simulation; industry 4.0; manufacturing.

I. INTRODUCTION

The new industrial revolution, most of the times referred to as Industry 4.0 or Smart Manufacturing has the potential to transform and reactivate the manufacturing industry in the USA [1].

Industry 4.0 is a term used to describe the vision of manufacturing systems integrated by processes with a high degree of automation, which are fully connected between them. The technologies that integrate this vision for manufacturing systems are: internet of things, robotics, automation, cloud computing, cybersecurity, data analytics, additive manufacturing (i.e., 3D printing), and simulation [2].

In recent years, the government of the USA was leading different initiatives to develop and implement smart manufacturing technologies. The goal of these initiatives is to generate new manufacturing opportunities within the USA and support the competitiveness of local manufacturers. For instance, the creation of the Clean Energy Smart Manufacturing Innovation Institute (CESMII) is one of these initiatives of the government focused on boosting Industry 4.0 technologies.

Inspired by public and private initiatives, a considerable number of manufacturing companies across the USA are trying to move from a traditional production floor to a smart production floor. Nevertheless, the introduction of Industry 4.0 technologies on the production floor is a challenging task since it is difficult to visualize how the production system will perform after the introduction of them.

Hence, the development of strategies to introduce Industry 4.0 technologies on the production floor is required. Consequently, the focus of this manuscript is to report the methodology followed and the findings of a project deployed in an assembly manufacturing company located in the USA that focused on the implementation of a manufacturing digital twin to predict the effects of introducing robotic systems in their production process. The rest of the paper is organized as follows. Section II includes a literature review of important concepts related to the developed project. In section III the manufacturing system is described. One can find in section IV the solution approach and the results obtained. Finally, in section V the conclusion of this manuscript is presented.

II. LITERATURE REVIEW

We will start by defining the concept of a digital twin. The concept was originally established by a NASA team [3][4], in this context, they defined the digital twin as a simulation model of a vehicle that integrates multi-physics, multi-scale, and probabilistic models. This digital twin uses physical models, sensor updates, and fleet history. Reference [5] describes a digital twin as a coupled model of a real machine that is available in the cloud and is used to simulate the health condition of that machine. Reference [6] defines the digital twin as a simulation model with the ability to describe events in time and space. These digital twins can be used during the design phases of the system and during the operational phases of the system.

A digital twin of a manufacturing system can be defined as a virtual representation of a manufacturing system that allows one to see how the system will perform in the real world; where the digital twin can be used to design, optimize and operate the system. In a manufacturing facility with Industry 4.0 technologies, the digital twin can be connected online through the Industrial Internet of Things (IIoT) and access in-real time the Enterprise Resource Planning (ERP) and the Manufacturing Execution System (MES) System updating the model according to the current status of the physical system.

One can find in the literature a limited number of case studies of digital twin's applications in manufacturing systems. Reference [7] reports the implementation of a digital twin to support manufacturing and maintenance planning in a roll shop. One can find in [8] the description of a plan to implement a digital twin in a drive shaft manufacturing plant.

 ISBN: 978-1-61208-831-0

Now that the concept for digital twin of manufacturing systems was established, we will define the concept of capacity analysis. One can define capacity analysis as the process used to measure the capacity of one operation in a manufacturing plant. More specifically, production capacity analysis refers to the maximum number of production orders that can be manufactured under specific conditions.

One can study problems related to production capacity analysis and optimization from different angles. For instance, reference [9] describes a case study of a production capacity analysis of a shock absorber assembly line where the configuration of the layout was modified to improve production rates. In this study, the production capacity was increased by 32%.

Reference [10] remarks on the lack of studies in the literature focused on the investigation of the influence and effects of limited buffer size in the production capacity of reentrant hybrid flow shops. The goal of this study was to develop scheduling strategies that will optimize production capacity. This type of problem demands a non-trivial solution since this problem is NP-hard. In this work, a hybrid harmony search and genetic algorithm were proposed.

III. OVERVIEW OF THE MANUFACTURING SYSTEM AND PROBLEM DEFINITION

As previously mentioned, the manufacturing plant presented in this manuscript is an assembly plant. The value stream of this manufacturing plant is composed of a complex internal structure where the workers currently perform all the processes with manual operations. The four main groups forming the processes of this facility are assembly, pre-painting, painting, and testing, where these groups have the flexibility to produce five different product types. One can find a schematic of this facility in Fig. 1.

The production processes of the assembly lines are configured as a hybrid flow shop. This is formed by a series of workstations, where some operations are performed in workstations with a parallel connection; the flow of this process runs in one direction.

The production processes of the painting area are arranged as a job shop with reentrances. The different products run through the painting shop in small batches of the same product type. Each product type requires a specific sequence with a specific set up. Not all the product types require to pass through all the processes, and most of the time a product needs to pass by a specific process several times. The workstations that perform the same function are grouped together. After the product types pass through all the required painting processes, they pass by a functional test.

As previously mentioned, one can classify the manufacturing operations of this system as manual operations. However, this manufacturing plant is on the journey of incorporating Industry 4.0 technologies into their processes. This manuscript reports the initial steps of this long-term initiative.

In this manufacturing system, some manual operations of the painting shop will be replaced with automatic operations performed by painting robots. The presented manuscript focuses on a capacity analysis with a limited buffer size prior to the implementation of these robots. The motivation for predicting the proper buffer size capacity prior to the implementation of these robots is based on the fact that these robots will affect the dynamics of the entire system and a proper buffer size needs to be determined. The buffers are located before and after the painting area.

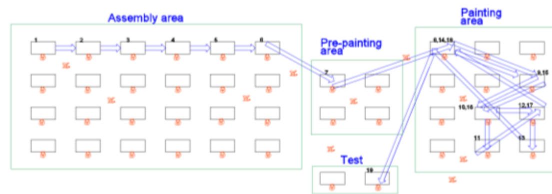

Figure 1. Assembly manufacturing plant.

IV. SOLUTION APPROACH AND RESULTS OBTAINED

The presented project was accomplished by systematically developing four key tasks. These four tasks are: definition of the logical model of the system, data collection, programming of the digital twin, and perform the analysis.

Task 1: Definition of the logical model of the system. The starting point to develop a digital twin of a manufacturing system is to define a logical model of it. Hence, the entire process of this manufacturing plant was mapped. In order to document the current state of the entire process, Value Stream Map (VSM) techniques were used [11]. VSMs were used because they offer an industrial engineering language that is well known around the world. After that, a spaghetti diagram was defined for each product type. One can see in Fig. 1 an example of a spaghetti diagram created for a product type. Different meetings were organized with the engineering group of this company to define the logical model generated for this facility for each product type. This process is typically interactive, especially for projects where it is required to develop a digital twin for an entire facility.

Task 2: Data collection. After the logical model was approved for each product type, the second task consists of working on the data collection and calculation of probabilistic distributions. This is a time-consuming process that requires a big effort [12].

It was found that the majority of the processes involving this production system can be modeled using triangular distributions. These are continuous probability distributions defined by the minimum value, most likely value, and maximum value.

Also, in order to accurately model the behavior of the painting robots, experiments with these robots were run to collect enough data to feed later the digital twin.

Task 3: Programming of the digital twin. Firstly, one needs to choose the proper software to program the digital twin. Simio simulation software was chosen for this project because this software offers the four discrete-event modeling paradigms developed for simulation of queuing systems; these paradigms are events, processes, objects, and agent-based modeling. Also, the Simio software is prepared to be connected online and driven by data received from the MES and ERP systems [2]. For this project, the digital twin was connected online to the

 ISBN: 978-1-61208-831-0

MES system, allowing starting the simulation as a non-empty and idle system.

The logical model previously defined in Task 1 was programmed using the Simio software. The paradigms that were used to develop the digital twin are objects, events, and processes. The programing task was divided into two phases. During the first phase, a digital twin that mimics the current state of the system was created to have a point of departure, which subsequently was used to develop a digital twin of the future state of the system. This digital twin was broken down into small parts and those were systematically programmed one at a time. Every time a small part of the digital twin was created, a verification analysis was conducted to prove that the model is behaving as expected.

Subsequently, the output of the digital twin of the system's current state was compared versus the output of the real system. The digital twin's programming, verification, and validation steps were done iteratively until the group of modelers and the engineering team of the manufacturing plant agreed that the digital twin was an accurate representation of the current system.

Also, a sensitivity study was conducted using linear regression. The input parameters that were chosen for the analysis are one station of the assembly and pre-painting areas, and the painting station. Fig. 2 shows a Tornado chart with the results obtained in the Simio software. The sensitivity coefficients of the previously mentioned workstations are 0.044, 0.039, and 0.018 hours, respectively.

Afterward, the programming of the digital twin of the current system was modified to mimic the previously defined logical model of the proposed system with painting robots.

Task 4: Perform the analysis. After the digital twin of the proposed process with painting robots was completed during the third task, the analysis task started. As mentioned before, this analysis focuses on quantifying the influence of limited buffer size in the production capacity of the proposed system with painting robots.

The presented study is focused on the calculation of the total number of products produced over the pre-defined buffer size of the painting area. In order to determine the influence of the buffer size, a what-if analysis was run.

The simulation runs for 365 days (i.e., 8,760 hours). An infinite demand was considered for this analysis, which means that it was considered that the system is able to ship all the units that are produced. For this analysis, the manufacturing orders of the product types were pushed through the value stream.

During the analysis, the average total number of parts was calculated for buffer sizes of 7, 8, 9, 10, 20, 30, 40, 50, 100, 200 and infinity.

Table I shows the average results obtained from fifty replications of the total number of parts produced. Also, one can see in Fig. 3 a graph that shows the total number of parts produced versus the different buffer sizes. It was observed that the system converges at a buffer size of 200, where the total number of parts produced with this buffer size is 5200 parts.

In terms of theory of constrains [13], one can say that the painting area is the governing constraint that determines the throughput, because this area has the processes with longest processing times and the manufacturing sequences involves re-entrance of the WIP of the different products. The system converges at a buffer size of 200 units because the buffer placed before this area ensures a starving time of zero for this area. At the same time, the buffer placed after this area allows a starving time of zero for the Testing area.

Furthermore, one can see in Fig. 4 the inventory of the cluster with painting robots. It is observed that for the case of an infinity buffer capacity the inventory in the robotic cluster grows without control, because of that, a limited buffer serves also as a production strategy to maintain the inventory levels.

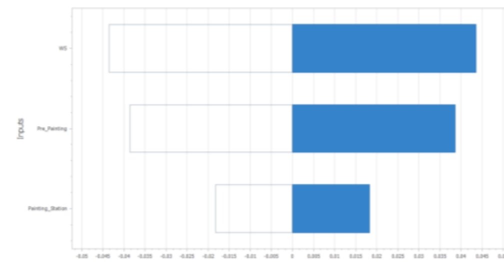

Figure 2. Sensitivity analysis of the selected processes.

TABLE I. NUMBER OF PARTS PRODUCED AS A FUNCTION OF THE BUFFER SIZE

Buffer size	Number of parts produced
7	4963
8	5006
9	5027
10	5065
20	5097
30	5129
40	5170
50	5185
100	5190
200	5200
Infinity	5205

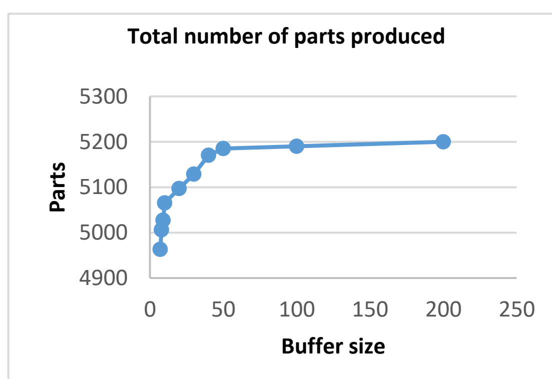

Figure 3. Total number of parts produced versus different buffer sizes.

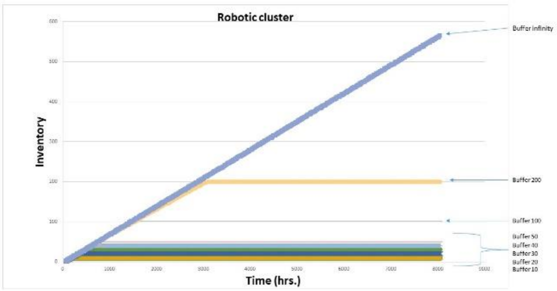

Figure 4. Inventory of the robotic cluster as a function of time.

V. CONCLUSION

In this manuscript, the initial efforts and findings of a company that is in the journey of incorporating Industry 4.0 technologies are presented. This research project reports an implementation of a digital twin of an entire manufacturing assembly plant that is used for design purposes. To be more specific, the digital twin was used to investigate the influence of the buffer size of the painting shop over the total production capacity for the future state of the manufacturing plant. The future state of the company consists on replacing some manual operations of the painting shop with painting robots.

The implementation of a digital twin enables us to quantify the influence of the painting robots before the insertion of them into the manufacturing system. The results of the analysis show that the system converges at a buffer size of 200, obtaining approximately a total number of 5200 parts produced. Also, it was observed that a limited buffer size helps to control the inventory on the production floor.

Furthermore, this manufacturing company will employ in the near future this digital twin as a foundation to quantify the different implications of adding additional technologies encompassed by Industry 4.0 on their production floor.

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