Simulation optimization for a flexible production process under uncertain factors

Fabio De Felice*, Cristina De Luca*, Ilaria Baffo**, Marta Travaglioni**, Antonio Forcina*, Antonella Petrillo*

**Department of Engineering, University of Napoli "Parthenope", Isola C4 Centro Direzionale Napoli 80143, Napoli, Italy (fabio.defelice@uniparthenope.it, cristina.deluca001@studenti.uniparthenope.it, antonio.forcina@uniparthenope.it, antonella.petrillo@uniparthenope.it)*

***Department of Economics, Engineering, Society and Business Organization, University of Tuscia, Loc.Riello, Viterbo 01100, Italy (ilaria.baffo@unitus.it, marta.travoglioni@unitus.it)*

Abstract: Today, the manufacturing sector is fundamental in all modern economic production systems. It represents a a complex sector adapting on the one hand to the needs of consumption, on the other to new production technologies. In such a competitive market it is necessary to develop flexible production models capable of increase efficiency to minimize costs reducing time-to-market and ensure on-time delivery. In this context, the new digital technologies are becoming more and more important to increasing efficiency in the manufacturing sector. Thus, the aim of the present research was to develop a simulation model based on the Digital Twin (DT) technology within a company in the manufacturing sector. The model made possible to predict the future performance of the physical asset. More in detail, the model was developed within an Italian SME that manufactures rack cabinet for electric vehicle charging stations. The company, in about a year, has tripled its monthly production to meet a strong market demand. This has pushed the company management to investigate the production process to improve it. Thanks to the simulation model, it was possible to analyze and control the operation of a process in real time, as well as evaluate any type of change before, during and after its implementation in order to assess its impact in terms of both advantages and disadvantages. The results of the real-world manufacturing are promising allowing managers to define future business strategies.

Keywords: Industry 4.0, Simulation, Digital Twin, Manufacturing process, Digital transformation

I. INTRODUCTION

Today, when we talk about innovation for manufacturing, we immediately think of Industry 4.0 and in particular of the dimension of digital innovation. In fact, the term Industry 4.0 indicates the transformation of the industrial sector in a digital perspective as well argued by several authors [1-3]. It is oriented toward the creation of an intelligent ecosystem based on the collection and processing of information about people, processes, services, and systems [4-5]. This new approach completely changes and turns the concept of manufacturing and the company upside down [6-7], driving a paradigm shift with the goal of increasing market supply and improving operational efficiency [8-10]. A successful manufacturing company must be agile, innovative, and highly efficient [11]. More companies have realized the conversion to an Industry 4.0 is a necessity [12-13]. This becomes a real challenge especially for small and medium-sized (SMEs) companies [14]. Digitization techniques can be used to succeed in the market and win the competition [15]. In this context, the process simulation plays a key role in this scenario. The current simulation modelling paradigm is best represented by the "Digital Twin" (DT) concept, that is a Key Enabling Technologies (KET) of industry 4.0 [16]. DT is a strategy within Industry 4.0 that operates on the principle of virtualization [17]. It is a key technology that enables a Cyber-Physical System (CPS) that can map and predict the operational state of a physical entity. CPS and DT are used to describe cyber-physical integration [18]. In manufacturing industries, DT can be introduced at any time in the production process [19]. It can be regarded as a planning and management tool; it allows optimize processes and products before they are executed due to its high-fidelity prediction capability [20]. The digital models are capable of self-diagnosis, self-optimization, and self-configuration without the need for human input or intervention in real time. DTs can be virtual representations of various systems, e.g., machinery, production lines, products, or any other operation or service related to the manufacturing process [21]. Several studies highlight the potential of using such technology. Zheng et al. [22] in his research proposes a DT system of a welding production line to improve product quality and production efficiency. The virtual model of the line is built by implementing real-time monitoring data collected. This ensures consistent interaction between physical and virtual production. Eriksson et al. [23] applies DT technology to conduct automation labs virtually in educational settings. An automation line is tested for an assembly task to explore the safety aspects and behaviour of the real system. Redelinghuys et al. [24] implemented a digital twin for an industrial manufacturing process specializing in the design and development of catalytic converter assembly lines. Specifically, the DT mimics a pneumatic belt-driven robotic gripper to evaluate its frequency and failure mode. Strachotová et al. [25] use a digital model to support a planner in compiling a line schedule. While Wu et al. [26] use simulation to verify the optimal layout to increase production capacity and efficiency. Therefore, the DT is an integrated system capable of simulating, monitoring, calculating, regulating, and controlling the state and process of the system [27], which allows to anticipate and contain the risks of their possible development [28]. The tangible benefits of this technology are manifested in cost reduction, shorter development cycle and increased product quality [29]. It is important to point out that the development of a simulation model simulated can be done with different tools. In fact, it is possible to use general purpose languages such as Pascal, C, C++, for which there are libraries of simulation-oriented routines or specialised languages, such as SIMSCRIPT, MODSIM and GPSS [30]. An interesting alternative is to use interactive simulation software's such as Arena, Witness, Extend and Micro Saint. These applications are easy to use and therefore very suitable for rapidly building even complex models [31]. In the present research Witness a commercial simulation software developed by Lanner Group is used [32]. In particular, this research examines a real production process in an Italian manufacturing industry that manufactures rack cabinet for electric vehicle charging stations.

A. *Objective of the study*

The contribution of this research is threefold. Firstly, it shows the potential of the digital twin and simulation as a decision-making and management tool in a complex production process. The development of the digital model allows an accurate and in-depth analysis of the process that would not be possible on the real process alone. Through the model it is possible to highlight process weaknesses (i.e. production delays, production interruptions, etc). Secondly, the present study suggests the digital twin as a powerful tool to drive digital transformation. Once the digital model has been developed, it can be used to test and validate the different technologies to be included within the production process for the conversion to smart industry. Thirdly, the research highlights that the digital twin can represent a key competitive advantage for SEMs enabling them to continue to operate in the market that is becoming increasingly frenetic and competitive.

The rest of the paper is organized as follows. Section 2 illustrates the mathematical formulation governing the discrete-time simulation implemented in Witness; Section 3 provides an overview of the developed simulation model and reference scenario; and Section 4 summarizes the main results. Section 5 discusses and analyses these results to evaluate possible solutions to the identified problems. Finally, Section 6 presents the main conclusions and future developments of the study.

II. MATERIALS AND METHODS

Witness software used to develop the digital twin is based on discrete-event simulation (DES). The main feature of discrete-event simulation is that it is events that trigger state transitions and temporal advances at discrete points in time. An event is defined as the completion of a task instead of any information transfer [33]. Thus, when any active task in the current state q is completed, the model makes a transition to state q+1 [34]. The information flow is modelled as entities. Activities are defined to process the entity (information). In other words, activities perform the different tasks. The total number of activities is equivalent to the number of tasks to be processed. Each activity processes the entity based on the sampled duration [35]. A DES system includes entities (EN) that are characterized by a set of attributes (AT). During the run phase, several system activities (A) are performed on system entities by the system resources (R). The system state (S) at each instant of time is described by a set of state variables (VR). The state of the system changes during the run phase upon the occurrence of a set of events (E). The model dynamics result in a time delay (D) and the system operation is controlled through the logical model (L) [36]. This mechanism belongs to discrete event simulation [37]. In the discrete-event mechanism, the events include the random arrival/departure of entities (elements) from/to service stations (machines). A Random Numerical Generation (RNG) is used to sample the inter-arrival and the service times (i.e. t and s) of the elements from the selected probability distribution. For each element arrival/departure, the model logic is executed based on a discrete-event and time-advancement mechanisms. At any simulation clock time T, an event is scheduled chronologically in the event list (EL) according to the following formulas:

$$A = T + a \quad [1]$$

$$D = T + s \quad [2]$$

The Arrival Time (A) is defined as the sum of the current simulation clock time (T) and the inter-arrival time (a). Whereas the Departure Time (D) is the sum of the current simulation clock time (T) and the service time (s). EL contains information about the event types and the time schedule of their occurrences [38]. It is formalised as follows.

$$EL = \{(E1,T1),(E2,T2),(E3,T3),\ldots(En,Tn)\} \quad [3]$$

III. MODEL DEFINITION

A. *Research methodology*

Research methodology is structured in 3 main phases and 7 steps as shown in Figure 1.

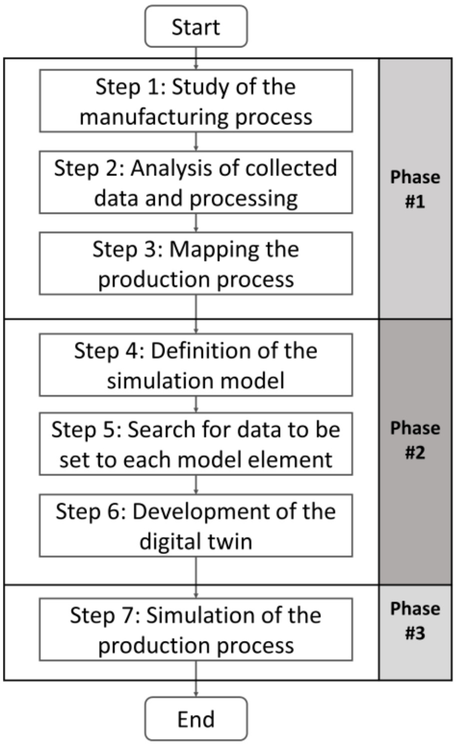

Fig.1. Phases of the research methodology

Here below a description of each phase is summarized:

- *Phase 1*: the aim of the first phase was to study and understand the production process carried out by the company. Data and information were collected through on-site inspections. For a detailed and concrete analysis, the collected material was classified and organised. At the end of this phase, the result was a mapping of the existing production process through a flow chart that is shown in Figure 2.
- *Phase 2*: The goal of this phase was to simulate the process *as is*. Starting from the current state of the production system, the scenario under study was designed. Once all the parameters were defined, the model was built in the Witness simulation software and simulated for a defined time.
- *Phase 3*: In the last phase the simulation outputs that were automatically generated by the simulation software were studied and critically analyzed. This activity led to the identification of critical points in the process and to the hypothesis of possible improvement solutions to be evaluated through simulation at the same time.

B. *Modelling scenario*

This research simulates the production process of an Italian company located in Naples (Southern Italy). The company manufactures rack cabinet for electric vehicle charging stations. Figure 2 shows some phases of the manufacturing process.

Fig.2. Phases of the manufacturing process

In about a year, customer demand has almost tripled. This has led the company to accelerate its production activity from a monthly production of one hundred cabinets to a weekly production of eighty pieces. Thus, an accurate study of the process and a well-planned activity has carried out in order to optimize new resources (i.e people, materials, etc.). The company produces various models of the same product, which differ mainly in the electrical power output and therefore in the size. In this research, the TX model is considered for the 50 kW DC fast charging station that can load all plug-in electric and hybrid vehicles. Typical charging times range from 15 to 30 minutes for DC charging. The cabinet is the result of assembling several elements. Figure 3 shows the TX model and its elements. Some of these elements are produced by the company itself while others are purchased from outside suppliers.

Fig.3. Cabinet TX and its elements

The production process is developed in two parallel activity flows that join in a final flow at the end of the process with an assembly activity as shown in the Figure 4.

As for the elements of the cabinet, the company produces the bases and roofs while the profiles are purchased already finished. As a result, laser cutting, part extraction, brushing, bending, and insertion activities are carried out for both elements. Sheet metal with a thickness of 4 mm is used to produce bases, while sheet metal with a thickness of 3 mm is used to produce roofs. The doors are purchased unfinished and then processed through a series of activities. In both process flows there is painting activity that is not carried out internally within the company but are outsourced.

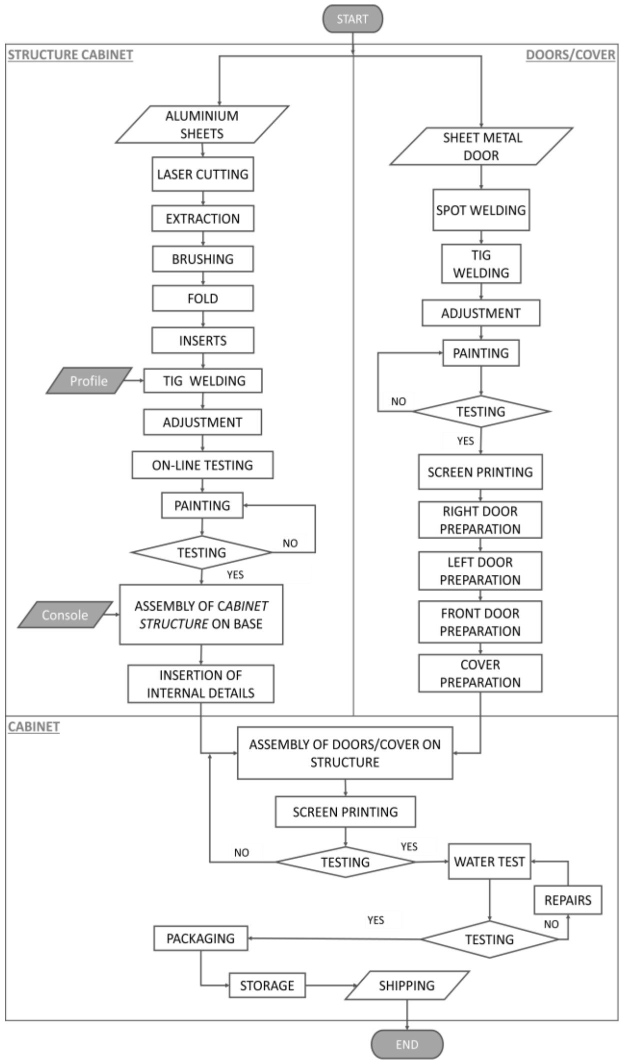

Fig.4. Flowchart Production Process of cabinet

C. *Simulation Model and description*

The digital twin model was constructed based on the flow diagram (Figure 4). It is important to note that digital model reports all mapped activities except *screen printing* and *brushing* as they are less than one minute long and therefore not relevant to the process. In particular, the model consists of *machines*, *parts*, *buffers*, and *Labor (workers)*. To develop the digital twin, the following hypotheses were assumed:

- Each activity is represented in Witness by a machine, these process the parts that go through the production flow.
- Some parts start the process while others are involved in it through the assembly machines.
- These last ones are stroked in buffers and from here recalled by the machines.
- Each system buffer has a capacity of 30 elements.
- As for the workers (Labor), some always work at the same workstation and perform the same activity, while others work at several workstations.
- The nature of most activities requires the presence of an operator, except for laser cutting and bending which are technologically advanced and state-of-the-art machines, all the others are labour activities.
- Although painting is an activity, as it is carried out externally to the business process, it is reported in the model as a buffer.
- For the activities that are part of the structure, the simulation was made considering the production of roofs, the bases are included in the welding phase together with the profiles as input elements of the activity.
- The production times of base and roof are equivalent to each other; therefore, the choice is purely random.

Table 1 shows the processing times for each activity and the distribution of workers. The time indicated is the average value of a series of time measurements carried out in the factory. The workers are indicated by increasing numbering. Aluminum sheet and Metal door are the parts that start the two flows of activity. Workers are positioned at the machines they work on.

TABLE I
SIMULATION INPUT DATA

FLOW	ACTIVITY	CYCLE TIME [*min*]	LABOR
STRUCTURE	Roof cut	5,51	1
	Removing parts Roof	7,50	1
	Roof folding	6,17	2
	Roof Preparation	6,90	3
	Insertion of inserts	6,68	3
	Structure welding	58,31	4
	Structure adjustment	59,24	5
	On-line testing	2,02	6
	Testing	5,20	6
	Assemblay Cabinet on Base	33,25	6
	Insertion of internal details	7,94	7
DOOR/COVER	Spot welding	12,99	8
	Door welding	5,44	9
	Door adjustment	3,03	9
	Testing	3,30	12
	Left door Preparetion	17,88	10
	Right door Preparation	19,67	10
	Front door Perparation	23,14	11
	Cover Preparation	37,04	11
CABINET	Assembly Cabinet	19,71	13
	Testing	7,18	7
	Water test	12,02	13
	Testing	4,59	13
	Packaging	8,02	12
	Storage	5,06	12

The model was organized following the structure of the production process. The first series of machines represents the flow of the *structure* while the second one refers to the flow of *doors/covers*. The machine "assembly" joins the two sequences and represents the point of departure of the last flow that finishes with the machine of storage. Figure 5 shows a model made in the Witness environment.

Fig.5. Simulation model in Witness environment

IV. RESULTS

The model is simulated for three different time intervals representing one day, one week and one month's work respectively. The number of cabinets produced according to the simulated production process is shown in the Table 2.

TABLE II
PROCESS OUTPUT AT DIFFERENT SIMULATION TIMES

TIME	TIME in minutes	NUMBER OF CABINETS
One Day	480	4
One Week	2400	37
One Month	9600	157

The simulation outputs obtained by simulating the process for one week are considered for analysis. Through the *Statistics* function of Witness, the simulation output data can be obtained. These data the results of the performance indicators that change according to the element of the process. Figure 6 shows the state of the machines in percentage terms in a 40-hour shift. The machine can be *busy*, which means it is performing its task, or *idle* and therefore waiting to work. It can be *blocked*, *full*, *empty*, and *waiting for a worker*. The machine can be in a *broken down* and/or *setup* condition that in turn can be influenced by the waiting for a worker. In this case, the last conditions are not present as they are not included in the break down or setup simulation.

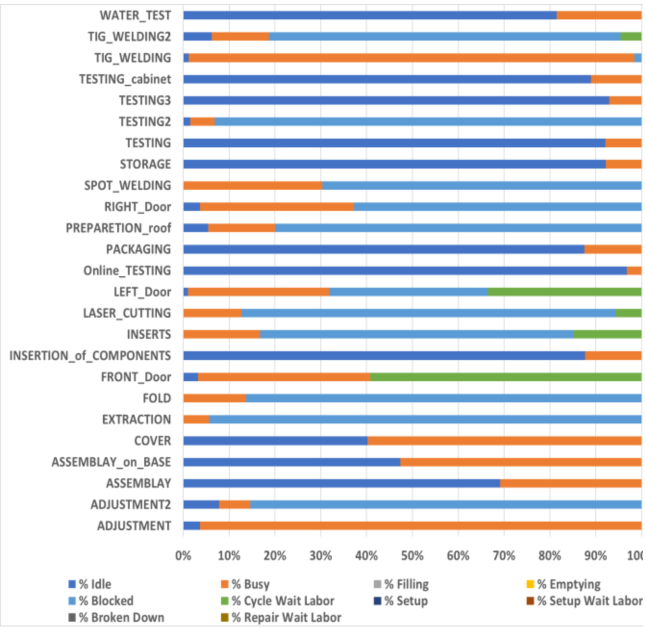

Fig.6. Machines Statistics

The state of the workers is shown in Figure 7 in tabular form. It is reported in percentage terms the availability of the workers (busy or idle) and information on the number (No.) of activities performed.

Name	% Busy	% Idle	Quantity	No. Of Jobs Started	No. Of Jobs Ended	No. Of Jobs Now	No. Of Jobs Pre-empted	Avg Job Time
Labo13	56.487	43.513	1	112.000	111.000	1	0	12.107
Labor1	18.278	81.722	1	110.000	109.000	1	0	4.019
Labor10	64.495	35.505	1	83.000	82.000	1	0	18.775
Labor11	97.416	2.584	1	78.000	77.000	1	0	30.000
Labor12	25.632	74.368	1	117.000	117.000	0	0	5.258
Labor2	13.651	86.349	1	54.000	53.000	1	0	6.170
Labor3	31.328	68.672	1	104.000	103.000	1	0	7.294
Labor4	97.209	2.791	1	41.000	40.000	1	0	58.310
Labor5	96.372	3.628	1	40.000	39.000	1	0	59.290
Labor6	63.787	36.213	1	115.000	114.000	1	0	13.423
Labor7	23.403	76.597	1	75.000	75.000	0	0	7.489
Labor8	30.333	69.667	1	56.000	56.000	0	0	13.000
Labor9	19.284	80.716	1	109.000	109.000	0	0	4.246

Fig.7. Labor Statistics

Finally, the last statistic shown in Figure 8 shows the conditions of the buffers. The information provided is mainly about the *number* of parts within the buffer and the *time* the parts spend in it, in different levels of detail.

Name	Buffers001	Buffers002	Buffers003	Buffers004	PAINTING1	PAINTING2	Q_BASE	Q_CONSOLE	Q_PROFILE
Total In	51	38	38	38	38	53	51	49	51
Total Out	41	38	38	38	38	43	41	39	41
Now In	10	0	0	0	0	10	10	10	10
Max	10	1	1	2	1	10	10	10	10
Min	0	0	0	0	0	0	0	0	0
Avg Size	9.474	0.000	0.000	0.883	0.000	9.387	9.973	9.969	9.973
Avg Time	445.851	0.000	0.000	55.755	0.000	425.062	469.309	488.282	469.309
Min Time	0.000	0.000	0.000	39.290	0.000	0.000	28.760	0.000	28.760
Max Time	592.900	0.000	0.000	72.220	0.000	601.800	592.900	710.240	592.900

Fig.8. Buffers Statistics

V. DISCUSSION

The development of the model allows to make some considerations as detailed below.

- Starting from the daily output, the expected weekly output would be 20 units, but a value approximately double is recorded. Thus, it is possible to deduce that the production process needs a set-up time.
- For buffers, it is possible to note that the capacity set for each one is 30 units with a filling time of 1.0 minutes. At the end of the simulation, the analysis shows that there are still elements in them and therefore their capacity is certainly not a reason to stop the machines being used.
- On the other hand, the statistics of the workers show a certain readiness. Examining these statistics with those of the machines, some blocked machines result due to the unavailability of a worker. A redistribution of machines can optimise the workers' activity and consequently the process. The constraint is the welding activities, which can only be carried out by specialised workers.
- The analysis of machine statistics is certainly the most complex. It is immediately apparent that many machines are blocked for a significant period of time. To better investigate this condition, the two main flows, structure, and ports/cover are studied separately. As with the whole process, output analysis is carried out. In this case, the output of the flow is defined as the element returned by each machine before the assembly activity in which structures are joined to doors/cover. Thanks to the

flexibility and simplicity of Witness, these results can be obtained quickly and are shown in Table 3.

TABLE III
OUTPUT OF THE FLOW THAT COMPOSE THE PROCESS

FLOW	NUMBER OF ELEMENTS
Structure	37
Doors/Cover	62

A. Analysis of findings and possible solutions

Further analysis and study of the results also shows that all activities before welding and adjusting are significantly blocked. In fact, even when analysing the data collected from the company's inspections, these two activities are particularly long compared to the others. A possible and immediate solution would be to double the two stations. Making this change within the simulation model, the outputs change significantly both for the entire production process and for the flow, as shown in Table 4.

TABLE IV
PROCESS OUTPUT AFTER ACTIVY CHANGES

FLOW	NUMBER OF ELEMENTS
Production Process	54
Structure	55

From the point of view of the state of the machines, the change made to the process shows improvements. Statistics show a 7-15% reduction in machine block for the entire process flow. For machines preceding critical activities this condition is reduced as follows: Laser cutting: 16%; Extraction: 7 %; Fold: 15%; Insert: 14 % and Preparation roof: 10%. Inside the plant, there are already other workstations and equipment for TIG welding and adjustments, but these are currently unused. The solution identified, therefore, is particularly valid. Those shown and discussed so far are only the first and simplest results obtained from a simulated model. However, in a digital transformation perspective, technological solutions could be implemented to replace two largely manual processes. For welding the introduction of a robotic system is planned. The new system can work 6 cabinets simultaneously in 10 minutes. For adjustment, two sensitized sanders that take 15 minutes per cabinet are planned. By implementing these machines within the digital twin, the number of cabinets produced changes significantly as shown in Table 5.

TABLE V
OUTPUT OF THE OPTIMISED PROCESS

FLOW	NUMBER OF ELEMENTS
Production Process	92
Structure	90

As for the state of the machines, again the changes made to the process result in improvements. The machine statistics preceding the two critical activities record a machine block reduction of 8-10% further than in the previous case. While the whole process reports a machine block reduction of about 20% which results in an improvement of the whole production flow. This is only the starting point for a longer and more detailed research aiming at process and resource optimisation and improvement.

VI. CONCLUSION

This research shows how simulation, and the digital twin can be valuable business support tools, particularly for SMEs that are already vulnerable and slow to change. In an ever-changing environment, finding a competitive advantage to resist the blows delivered by the manufacturing ecosystem is necessary. Witness, software of simulation to discrete event, is used as powerful decision-making tool. The development of the digital model allows to have a vision "from the top" of the process without hindering or intervening in any way on the production. At the same time, the *What-if analysis* allows to validate and test different solutions until intercepting the one that optimizes the result in terms of cost, primary resources, manpower and time. In particular, with a view to digital transformation, this analysis can represent a guideline for the digitisation of processes. The dynamic simulation provides an objective evaluation of alternative solutions of which it is very difficult to predict the behaviour, performance, and impact on other systems. This makes it possible to respond to the strong business need to have tools for the anticipation, sizing, and containment of project risks. Having tools such as the digital twin and simulation allows one to anticipate and be ready for any change. The digital model becomes the solution for the development of innovative projects for which experience is no longer a reliable and sufficient tool to face the uncertainties of the future. In fact, experience has matured in the past. In this perspective, future research could concern the study for the implementation of new production technologies within the company. With the use of simulation, it would be possible to develop a cost-benefit analysis for the possible integration of robots, augmented reality, sensors, cloud for a meaningful conversion into a smart manufacturing.

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