DISCRETE-EVENT SIMULATION OF CERAMIC TILE MANUFACTURING FOR GENERATING ITS DIGITAL MODEL

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ABSTRACT

The first step in the transformation process that an industrial company must undergo in developing Industry 4.0 capabilities involves obtaining a so-called digital twin of its different internal processes. In the production context, currently available technologies enable all events and states in the production process to be recorded in real time. This provides an updated digital model of the factory, known as a digital twin. In this study, a methodology has been developed and implemented to generate a digital model of the ceramic tile manufacturing process. To do so, different technologies were used that allowed a cyber-physical system of the manufacturing environment to be created, based, on the one hand, on collecting process data, supported by a product traceability system and, on the other, on a dynamic simulation and modelling process using the discrete events technique.

1. INTRODUCTION

In increasingly competitive markets, improvement of decision-taking mechanisms associated with digitalisation of the manufacturing processes entails a great opportunity for optimising company productivity and efficiency. Industry 4.0's economic potential therefore lies in its ability to accelerate decision-taking and adapt organisation internal processes to the changes in their environment, thanks to continuous analysis of large volumes of data and the interconnection of cyber-physical systems and individuals [1].

1.1. THE DIGITAL TWIN

The current advanced degree of instrumentation in industrial processes facilitates data collection throughout the production cycle and allows all events and states occurring in a process to be recorded in real time. This enables development of a constantly updated, digital model of the factory, known as a digital twin [2]. The interest in having a digital twin of the manufacturing process lies, on the one hand, in knowing in real time what is happening in the process and, on the other, in managing decisions based on analysis of information generated in the digital twin. Numerous studies have shown that deployment of this tool is a basic step on the road to transformation towards Industry 4.0 [3][4].

In this context, the digital twin constitutes a virtual, dynamic representation of the production system. This representation is able to keep itself perfectly synchronised with the physical system thanks to the combination of mathematical models and real-time processing of the data facilitated by process instruments. The combination of the digital twin and represented physical environment constitutes what is known as a Cyber-Physical system [5] (see Figure 1).

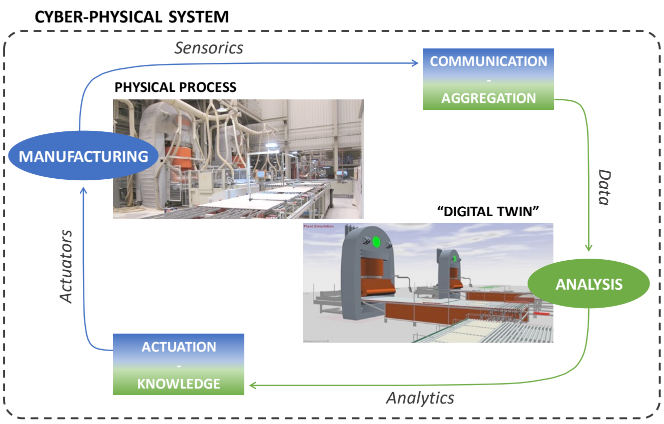


Figure 1. *Cyber-physical system in a production setting on integrating the digital twin and the physical world.*

Having a digital twin of a manufacturing process enables simulation and optimisation of the production system, contributing to greatly enhanced competitiveness, productivity, and efficiency. In addition to these essential aspects of production management, if the digital twin includes models of product performance throughout the manufacturing process, the product's physico-chemical properties can be evaluated across the process and interrelated with production variables.

This possibility not only helps to improve production efficiency, but also to increase end-product quality and to keep it at optimum levels.

Obtaining a digital twin requires a series of preliminary steps linked to the potential degree of integration between the physical process and its virtual copy (see Figure 2). First, it is essential to have a digital model, i.e. a digital representation of the physical process, which uses no type of automated data exchange between the physical world and the digital environment. These models can be made up of simulation models, mathematical models, or any other type of model of physical objects using no type of automatic data integration.

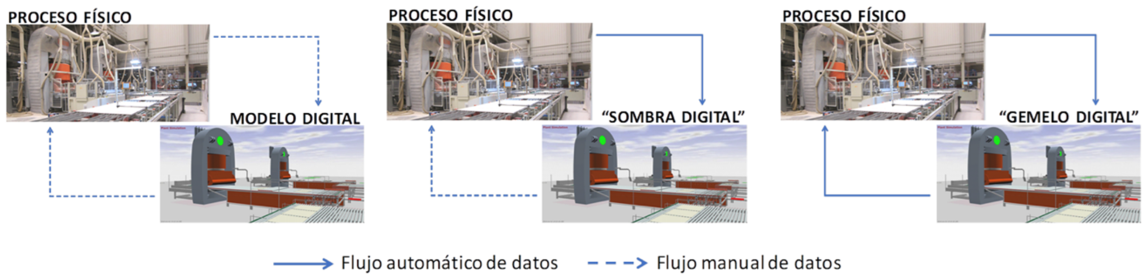


Figure 2. *Possible information flows between the physical process and the related digital process depending on degree of integration attained.*

Once the digital model of a process has been deployed, its digital shadow can be generated, thanks to implementation of an automated, one-way flow of data from the state of the physical process to the digital world. In this situation, a change in the state of the physical process leads directly to a change in the digital process, but not vice versa.

Finally, full two-way integration of the data flow between the physical and the digital process yields a digital twin. In this situation, the digital process performs control actions on the physical process, such that a change in the physical process leads directly to a change in the state of the digital twin and vice versa.

Implementing a digital twin in a ceramic company is a great challenge, fundamentally, because information is generally decentralized in different data islands, there often not being just one valid source [6]. However, from the standpoint of the manufacturing process, recent years have witnessed significant progress in the integration of data from different production units. In fact, there have been several pilot experiments, such as the one described in [7], which demonstrate the possibility of full integration in a ceramic plant of the industrial data relating both to the critical variables of each process stage and to the operating variables of the equipment. In view of this situation, this study explores the possibilities of generating a digital model of the ceramic tile manufacturing process using open-source simulation and visualisation tools, which lay the groundwork for obtaining a digital twin in the near future.

1.2. DYNAMIC DISCRETE-EVENT SIMULATION

Ceramic tile processing, from tile forming to packaging, fits perfectly into the discrete process typology. Unlike continuous processes, in which the state of the system changes continuously in time, discrete processes consist of a series of sequences or events that take place at a given moment in time. Continuous processes customarily involve transformation operations in which fluids are handled, e.g. in chemical plants such as oil refineries. On the other hand, examples of discrete processes include most manufacturing processes, transport systems, and public systems such as hospitals or public administrations, and all processes and systems that involve queue management.

The digital model proposed in this study was generated using a simulation technique called discrete-event simulation (DES). This methodology allows a given system to be modelled as a (discrete) sequence of events in time. During the simulation, each event represents a change in the state of the system, it being assumed that, between two consecutive events, there is no change in the events [8]. Generally speaking, the DES is used to model systems that require managing queues. The system is represented as entities that flow between the different process activities in which queues can appear. The queues fill up with entities when the entities reach a certain activity at a higher rate than the rate at which the activity can process them.

In a DES model of the ceramic process, ceramic tiles would be physical entities that flow through the transport systems, stackers, storage systems, and processing equipment making up the different lines in a ceramic plant. The queues, for example, would be the park of guided kiln cars between the glazing and firing sections, the vertical storage buffers usually found in different parts of the manufacturing lines (commonly known as "compensers"), or row formers of tiles, generally at dryer and kiln entrances.

A DES model can be implemented using specific libraries developed for high-level programming languages such as C++ or Python®. However, in this study, an open source tool called JaamSim® has been used [9], whose use requires no advanced programming knowledge and allows very useful solutions to be obtained in relatively short development times. JaamSim® (Java Animation Modelling and Simulation) is a discrete-event simulation software whose development began in 2002. The package includes a graphic user interface, a 3D animation engine, and a complete set of objects and utility functions for constructing simulation models. An object-oriented solution is involved, which is extremely rapid and scalable up to applications of considerable size (models with more than 300,000 entities have been tested at acceptable processing rates). Together with requiring only a short learning time, the other reason for choosing JaamSim® for this study was that, as an open-source package, the programming code is distributed free. This will, in the future, allow modification or creation of objects and modelling methods that, if necessary, enable developments achieved to be adapted to the specificities of the tile manufacturing process.

2. IMPLEMENTATION OF THE DIGITAL MODEL

2.1. GENERAL CHARACTERISTICS

The digital model developed by DES is made up of two forming and decoration lines, both having the same production capacities. Each line consists of a hydraulic press with a maximum pressing capacity of 64000 kN, a 20-metre-long horizontal dryer, 5 drying planes, with 3.7-metre useful width, and a glazing line with various decorating applications. The process is rounded off with a storage area for unfired and fired material, and a 130-metre-long single-deck roller kiln with 2.7-metre useful width (see Figure 3). For simplicity's sake, in this first development, the sorting and end-product packaging sections were not included, though it should be noted that the JaamSim® tool would allow their implementation in the model.

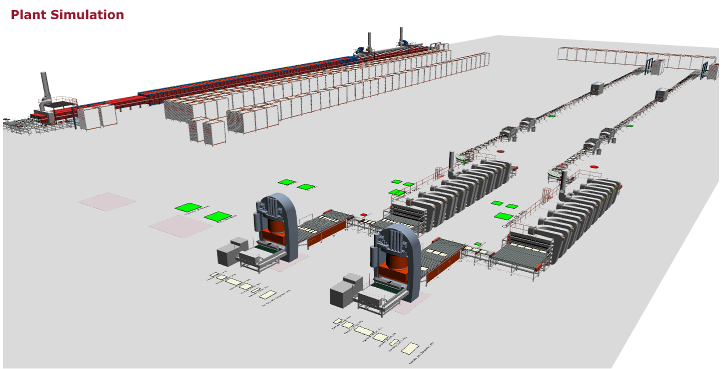


Figure 3. 3D views of the developed digital model.

The model was designed to simulate the manufacture of lots of porcelain tiles of 5 possible fired nominal sizes: 30 cm x 60 cm, 60 cm x 60 cm, 60 cm x 120 cm, 25 cm x 75 cm, and 75 cm x 75 cm. To do so, a production regime of 3 shifts/day, 5 days a week, in the forming and glazing sections; and 3 shifts/day, 7 days a week, in the kiln was defined, which would allow a theoretical capacity of about 8,000 m2/day to be reached.

Together with all the equipment used in executing the process stages considered, the model includes all transport systems required in handling the product between the stages. It thus allows simulation of tile transport across the press exit rollers, the row formers at the dryer and kiln entrances, the conveyor belts of the glazing lines, and storage and transport in the kiln cars, among others. By way of example, the images in Figure 4 show, on the one hand, a 2D visualisation of the part of the digital model corresponding to the pressing section and the start of the decoration lines and, on the other, a schematic view of the same region of the model, showing the different block diagrams and modules in the JaamSim® programming environment.

To parameterise the model, a series of heading files were defined for each tile size to be made. These files include, for example, the theoretical speeds of the different transport elements; the number of tiles processed per row in the press, dryer, or kiln; the number of tiles per row and plane contained in the storage cars; and drying and firing cycle time. In addition, for the digital model to allow simulation of actual operating conditions, an initialisation file was generated that contained the planning to be effected in the different forming lines. Thus, for each press, the planned manufacturing orders were set out in sequence, with the size and number of square metres to be made in each case.

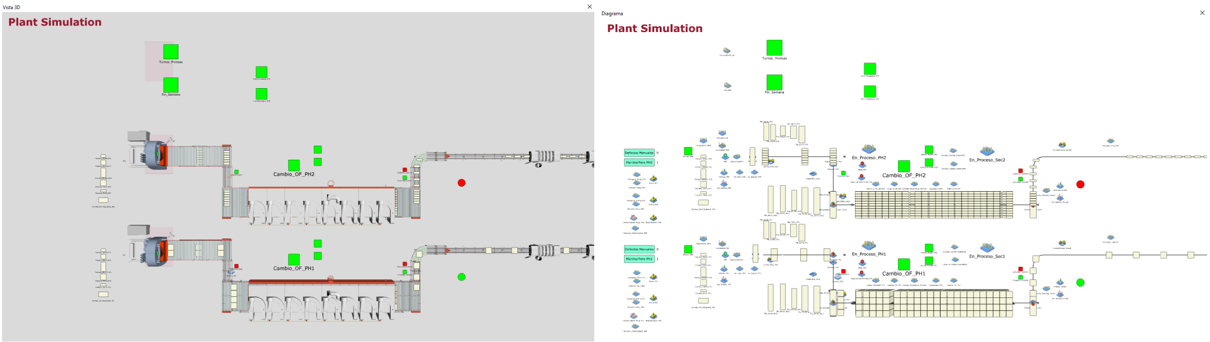


Figure 4. *Views of the forming section implemented in the developed digital model. Rendered visualisation (left) and view in the development scheme (right).*

2.2. INCORPORATION OF VARIABILITY IN THE SIMULATION

The model was equipped with the variability associated with the industrial processes in order to take into consideration stoppages and losses in production output owing to breakdowns in equipment, preventive maintenance actions, production wastage, interruptions owing to incidences in transport lines, stops for model changeovers, and stops relating to size changes in the product being fabricated. This allows simulation of the evolution of typical production metrics, such as availability, efficiency, and quality, which contribute to production line overall equipment efficiency (OEE) [10]. Variability was implemented using the probabilistic functions provided by JaamSim®, programmed using algorithms adapted from [11]. These functions enable random generation of data that are adjusted to a certain probabilistic distribution, with a view to simulating the effect of all the above variables. The selection of the probability function used in each case was performed by analysing the data generated by the traceability system fine-tuned during performance of the project described in [7]. The variability included in the model is described below; the probabilistic functions used are summed up in Table 1:

- Modelling of the variability associated with process stoppages

  The variability associated with stoppages, whether planned or unexpected, directly affect equipment availability. Stoppages were modelled considering stoppage frequency and duration.

- Modelling of production rhythm variability

  Although production equipment usually works at constant operating speeds in actual manufacturing conditions, when it comes to modelling the process it is interesting to incorporate a certain variability into this speed in order to absorb certain process stops that, owing to their short times, are difficult to model in the mode described above. Proceeding in this manner, the effect of so-called micro-stoppages on production equipment efficiency can be modelled.

- Modelling of production wastage

  Production wastage directly affects production quality. To reflect its incidence at different points of the manufacturing lines, the generation of losses was implemented by a Boolean generator that modified a property assigned to each processed tile, indicating whether it was defective or not. The probability that a tile was deemed defective was fixed by a mathematical function.

Type of variability	Variables modelled	Probability functions	Examples
Variability in line stoppages	- Stoppages in manufacturing lines - Breakdowns	Stoppage frequency: Erlang distribution Stoppage time: log-normal distribution	Non-planned press shutdown: Frequency: Erlang distribution Form factor = 1 Average = 1 h Duration: log-normal distribution MeanNormal = 0 STDNormalDeviation = 1 Scale-up = 10 min
	- Programmed maintenance	Stoppage frequency: defined time series Stoppage time: log-normal distribution	
Variability in production rhythm	Production rhythm changes in: - Presses - Kiln	Discrete distribution	Pressing rhythm: Maximum rhythm percentages related to a probability Perc. (%): 100 95 90 85 Prob. (%): 25 50 20 5
Variability in generated loss	Loss in: - Presses - Decoration - Park - Kiln	Coupled continuous sine function with a Boolean generator or discrete distribution	Defects generated in press: $y(t) = 2000 \sin(2 \Pi t/T)$ T = 45 min

Table 1. *Summary of the probabilistic functions used in modelling model variability.*

3. APPLICATION OF THE DIGITAL MODEL

Lot	Planned amount (m²)	Manufacturing time (h)		
		Condition A OEE = 61.8%	Condition B OEE = 65.2%	Condition C OEE = 66.7%
1	5,500	14.4	14.3	13.8
2	3,500	11.3	9.8	9.5
3	4,000	13.4	11.7	11.5
4	3,500	12.5	11.9	11.3
5	5,500	21.6	19.9	19.9
6	4,500	18.9	15.1	14.1
7	4,500	18.5	18.1	14.4
8	2,000	-	10.4	8.5
9	2,500	-	-	9.0 (87% of total)*
Total (m²)		30,998	32,997	35,199
Loss (m²)		1,017	1,183	302
Stops (h)		38.4	34.6	34.8

Table 2. *Lot planning and simulation results for a forming line (*unfinished lot).*

To evidence the applicability of the developed model, several case studies were addressed that illustrate how this correctly reproduced the performance of the manufacturing process. First, production in one of the model's forming lines was simulated, during an entire week, under different process variability conditions. During the studied time, the incidence of the losses and line stoppages was evaluated, recording the production metrics of quality and availability [11].

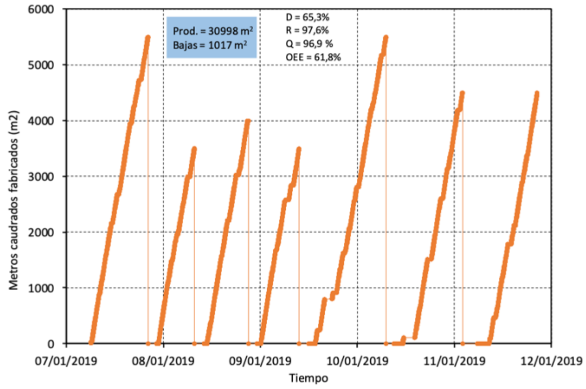
To do so, a planning was defined (see Table 2) of several lots of tiles with nominal fired size of 60 cm x 60 cm, with different target product quantities to be formed, and the evolution of the simulated production was observed. Note that, for simplicity's sake, in applying the model, possible changes in equipment performance were not considered, even though the model is able to simulate these.

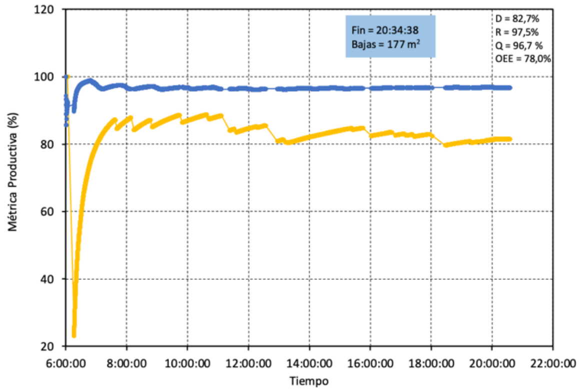
In particular, as may be observed in Table 2 and Figure 5, three different variability conditions were evaluated, corresponding to an average forming section OEE of 61.8%, 65.2%, and 66.7%, respectively. In the first condition (condition A), a low OEE value was obtained by increasing the frequency and duration of the stoppages described in Table 1, which resulted in low equipment availability during the simulated period (65.3%). In the second condition (condition B), availability rose noticeably (68.9%) and quality remained at very similar levels to those of the previous case (97%). Finally, the last simulated condition established the best OEE, as a result of a similar availability to that of the previous case, but a very high quality (99,3%), obtained by reducing the number of defective tiles generated in the press.

The graphs on the left of Figure 5 show, for the simulated week, the evolution with time of forming section production, under the three conditions considered. As the simulations developed, for a certain lot, the number of square metres produced increased progressively up to the planned total amount. Manufacture of a fresh lot then began, illustrated in the graphs by the "sawteeth" displayed in the graphs. The periods of time during which the square metres produced remained at zero values corresponded to times devoted to changeovers of the manufacturing lot and to performance of the corresponding adjustments. The graphs indicate, for each condition, the total number of square metres made during the week, the arising wastage (m^2), and the average production metrics. As was to be expected, the condition that allowed the largest number of square metres to be produced during the simulated week was the highest OEE condition (condition C), at 35,199 m^2. According to the model, under these conditions, the line could make 8 of the planned lots and much of the ninth lot. The worst condition (condition A), owing to the greater incidence of unexpected stoppages and downtimes for lot changeovers, would only allow 30,998 m^2 to be made, corresponding to 7 of the planned lots. Condition B, with an intermediate OEE, would allow 8 entire lots to be made, equivalent to 32,997 m^2.

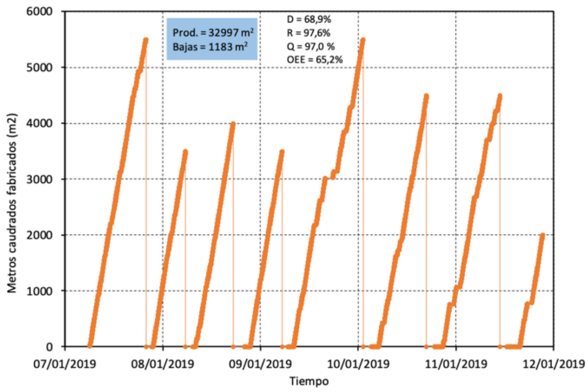
On the other hand, the graphs on the right of Figure 5 show the evolution in time of the quality and availability metrics corresponding to the first lot simulated in each condition. To be able to depict the data with the greatest clarity, the time devoted to performing the adjustments and preparations before fabricating the lot was not considered. The availability values of the lot were therefore notably higher than the week average, resulting from including the data of several lots. Together with the average production metrics of the lot, the graphs show lot finishing time and arising manufacturing wastage (m^2). The simulation performed under the best OEE conditions was that which allowed the planned production quantity (5,500 m^2) to be made in the shortest possible time, specifically in 13.8 h, thanks to the low wastage. On the other hand, the simulation carried out under the lowest OEE conditions (condition A) was the one that predicted the longest performance time (14.4 h), owing to low equipment availability.

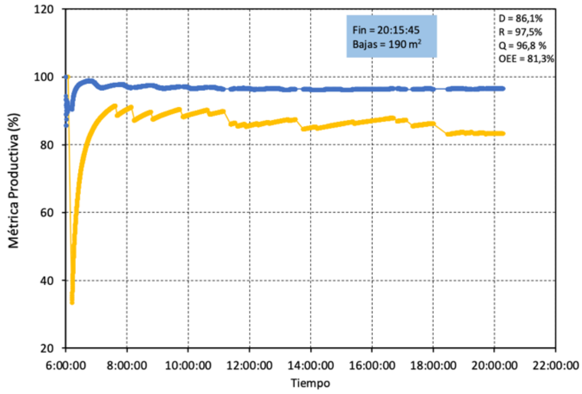
CONDITION A



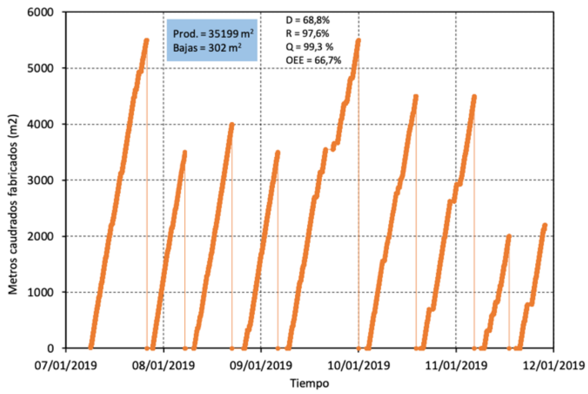


CONDITION B





CONDITION C



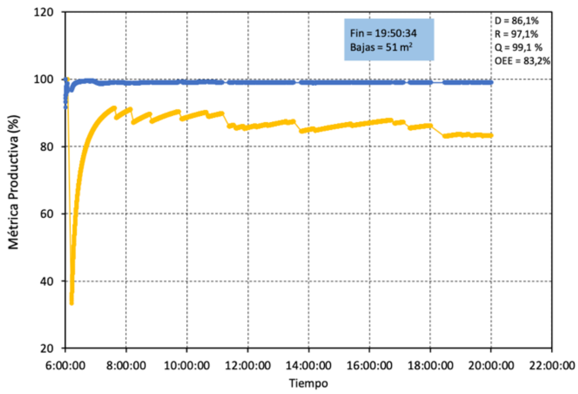


Figure 5. *Simulation of forming line productivity. D: Availability; R: Efficiency; Q: Quality. Left: evolution of the amount of formed product, by manufacturing lots. Right: evolution of availability (yellow) and quality (blue) of a manufacturing lot.*

In these graphs it is interesting to note how the model allowed the evolution of production metrics to be tracked under different simulated conditions. Thus, for example, the effect of greater stoppage frequency and duration under condition A, was reflected in a greater point reduction of availability (yellow line) in the first recorded significant stoppage at about 06:15 h, with respect to the graphs of the other two conditions. Similarly, the greater generation of wastage in conditions A and B, relative to C, was evidenced by stabilisation at lower production quality values (blue line) on finishing the studied lot.

The above example illustrates, in a simple way, the model's potential for simulating the tile manufacturing process. However, the true interest of such a tool lies in the simulation of production situations of greater complexity, in which multiple production elements and manufacturing lots with different tile sizes are combined. Consequently, using the full model, simulations were performed under three different plant operating conditions. The calculation was initialised with the same planning in the forming lines: 30 lots of tiles of nominal fired size 75 cm x 75 cm and 60 cm x 60 cm in forming line 1; and 30 lots of tiles of size 30 cm x 60 cm and 25 cm x 75 cm in forming line 2. In both lines it was assumed that two changes were made in fabricated tile size ("format" changes), production starting in press 1 with 60 cm x 60 cm tiles and in press 2 with 25 cm x 75 cm tiles.

In this case, for the three simulated conditions, the same efficiency and the same amount of wastage were maintained, modifications only being considered in equipment availability. In addition, to simplify the interpretation of results, in calculating kiln availability, the fact that availability was not considered to be affected by lot and/or tile size changes was adopted as a simplification.

As may be observed in Table 3, the most unfavourable situation corresponded to condition D, in which the plant was equipped with a 130-metre-long kiln. Although the kiln ran at practically its maximum availability (99.7%), indicating that there was always unfired material in the buffer for kiln feed, the short kiln length significantly penalised plant productivity. Indeed, to produce a total of 213,180 m^2, at an average of 7,860 m^2/day, the plant needed 27.1 days. In addition, the low availability of the forming lines (51.2% and 45.1%) was related to the fact that, at the end of week (Thursday and/or Friday), there were no free kiln cars in the buffer for storing more unfired material]

In condition E, plant productivity improved noticeably, reaching production of 8,480 m^2/day, achieved owing to use of a longer kiln (170 m). In this situation, though the two presses displayed slightly higher availability than in the previous case, sufficient products could not be made for the kiln to be fed every weekend. Hence the observed drop in kiln availability (87.1%).

	Cond. D	Cond. E	Cond. F
Kiln length (mm)	130	170	170
Manufacturing time (days)	27.1	25.0	22.2
Total production (m^2)	213,180	214,050	213,090
Productivity (m^2/day)	7,860	8,560	9,600
Kiln availability (%)	99.7	87.1	99.6
Line 1 availability (%)	51.2	55.0	62.9
Line 2 availability (%)	45.1	49.2	55.2

Table 3. *Results of the simulations for the full model under three different operating conditions.*

Finally, in the simulation corresponding to condition F, better results were obtained, only 22.2 days being needed to make all the planned lots, with an average productivity of 9,600 m^2/day. In this case, kiln length was also 170 m, but the statistical incidence of the forming and decoration line stoppages were modified to increase their availability, which maximised kiln availability (99.6%) on being continuously fed every weekend.

The second case study showed the usefulness of the developed digital model for making predictions that help improve in-plant decision-taking. The model can be coupled to an optimisation algorithm to simulate multiple possible scenarios based on modification of the input parameters, thus providing results that better adapt to particular needs at a given moment. The technique is very efficient, enabling simulation of complex situations, such as those described, in a matter of minutes. Thus, for example, each simulation of the second case study was run in 4 minutes on average, using a conventional computer with an Intel Core i5 processor and 8 GHz RAM memory.

4. CONCLUSIONS AND FUTURE WORK

The following conclusions may be drawn from the study:

- A digital twin is deemed a key tool for implementing Industry 4.0 standards in any manufacturing process.
- A digital model of the ceramic tile manufacturing process was developed, based on use of the dynamic modelling technique of systems by discrete events, using the free software tool JaamSim®.
- The developed model was successfully applied to study forming line productivity and management of a complete plant under different operating conditions.
- The discrete-event simulation technique proved to be very efficient in simulating complex situations in the ceramic tile manufacturing environment.

The resulting validation of the applicability of the DES technique for modelling the performance of the ceramic tile manufacturing process enables several future work possibilities to be envisaged. First, automatically integrating the developed digital model into an actual manufacturing process, via a standard communication protocol, such as OPC-UA, to obtain its digital shadow. And secondly, based on this digital shadow, establishing procedures that allow direct interaction with the physical process, to obtain its digital twin.

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